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ABSTRACT

This concept module on energy convertors is one of thirteen modules that provide a flexible, laboratory-based physics instructional package designed to meet the specialized needs of students in two-year, postsecondary technical schools. Each of the thirteen concept modules discusses a single physics concept and how it is applied to each energy system. This module discusses (1) a variety of energy convertors, important in the conversion and application of energy, and (2) the efficiency of the individual energy convertors and systems. Included with the concept module are thirteen application modules that discuss a specific application of a single concept in a single energy system, and contain a student laboratory exercise. Laboratory modules included are Turbines, Fluid Pumps, Fans and Blowers, Wind Power, Vacuum Pumps, Electric Generators, Alternators, Electric Motors, Solenoids and Relays, Photovoltaic Materials, Boilers, Thermoelectric Generators, and Solar Collectors. (LRA)

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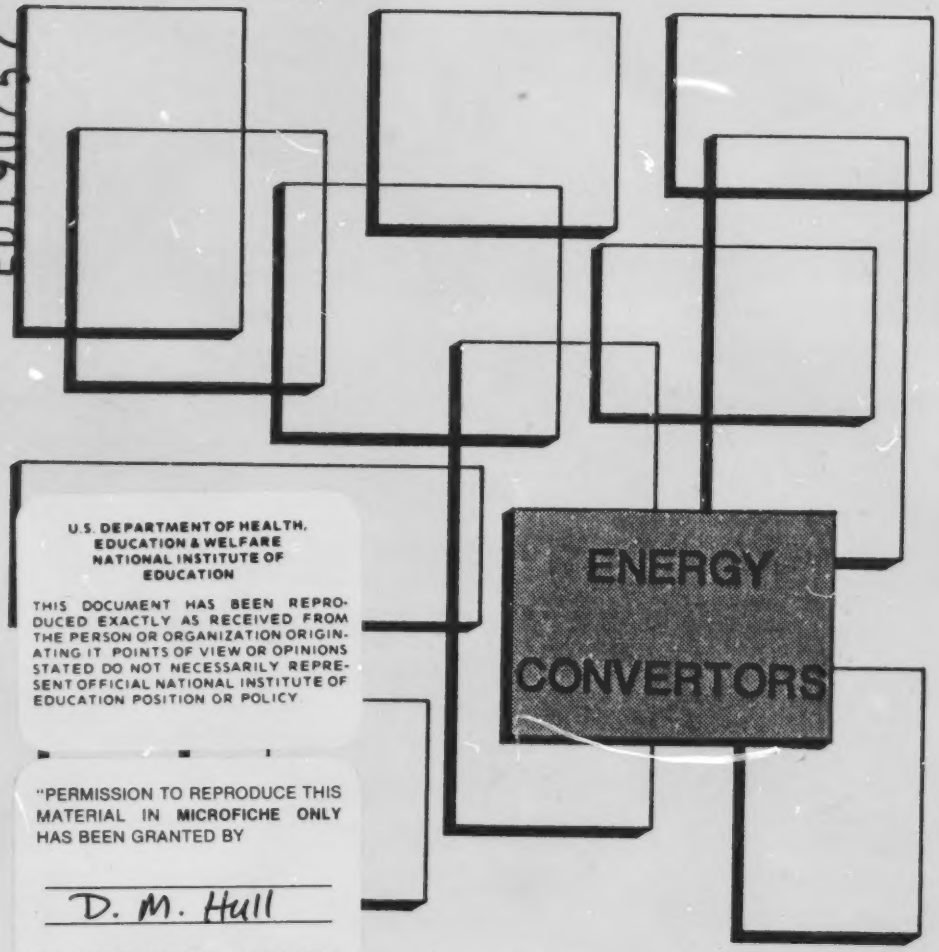
# UTC

UNIFIED TECHNICAL CONCEPTS

CONCEPT MODULE 9-0

ED190757

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## INTRODUCTION TO UTC

Complex, modern equipment often contains combinations of hydraulic, pneumatic, thermodynamic or optical subsystems, as well as mechanical and electrical components. These subsystems and components appear not in isolation but as interdependent parts of complex systems. Consequently, a modern technician must understand not only the separate subsystems but also their interrelationships and the roles they play in an integrated system.

Since physics provides the foundation for modern technology, physics instruction in technical programs cannot be overemphasized. Physics courses for technicians should achieve three major objectives:

- Provide students with all the basic physics principles that apply to their chosen field
- Reinforce these principles through the use of "real" examples and hands-on experience.
- Organize knowledge and skills gained in a manner that provides ease of application in solving systems-oriented problems.

These objectives must be accomplished in a minimum of instructional time, and in a manner flexible enough to meet the needs of a variety of technical specialties.

Unified Technical Concepts (UTC) is a flexible, laboratory-based physics instructional package designed to meet the specialized needs of students in two-year, post-secondary technical schools. UTC organizes technical physics into 13 basic concepts (Force, Work, etc.) that apply in four "energy systems" (Mechanical, Fluidal, Electrical, Thermal). Each of the 13 "concept" modules discusses a single physics concept and how it is applied to each energy system. Similarly, each "application" module discusses a specific application of a single concept in a single energy system, and contains a student laboratory exercise.

The recommended prerequisite for UTC is one year of high school algebra, but eight supplementary modules are available for students requiring additional skills or review in the areas of math, units and graphing.

UTC is an alternate method of presenting what heretofore has been a formidable and sometimes confusing subject for technicians. It provides laboratory experiments that apply to specific technological fields, which allows a student to relate more quickly to module content - to understand how it applies to a specific technology.

UTC also represents a unique approach to teaching applied physics. Its flexible modular format allows it to be tailored by physics and technology instructors to meet

specific needs of students in a specific technology.

## STRUCTURE OF UTC

The modern world is based on the control and application of energy. Technology is the means by which that energy is applied to accomplish a desired task. Technical physics, being primarily a study of the physical basis of the control and use of energy, can be categorized according to the type of energy involved. Thus, in UTC, physics is divided first into four "energy systems" - Mechanical, Fluidal, Electrical and Thermal.

The same divisions are characteristic of traditional approaches to teaching technical physics. A student usually begins by studying mechanics. Once this branch of physics (energy system) is mastered, electromagnetism, thermodynamics and hydraulics are studied (one energy system at a time).

UTC takes a different approach.

### CONCEPTS IN PHYSICS

The basic ideas, or "concepts," of physics appear in all energy systems, and these concepts relate to one another in similar ways in all systems. UTC unifies technical physics by presenting first the physics concept and then its application in each energy system.

The first concept studied, for example, is that of force, - the physical quantity that produces motion. The basic characteristics of force are followed by a discussion of how this concept applies to "forcelike quantities" in the following energy "systems":

- In mechanical systems <u>force</u> and <u>torque</u> cause motion of mass.
- In fluidal systems <u>pressure difference</u> causes motion of fluids.
- In electrical systems <u>potential difference</u> causes motion of mass.
- In thermal systems <u>temperature difference</u> causes motion of heat energy.

Problems, demonstrations and hands-on laboratory exercises are used to show the application of the concept in each energy system, and to specific devices or processes common in modern technology.

Thus, UTC provides a student with the basic concepts of physics reinforced by practical application and organized into a consistent whole; UTC is readily applied to future technical problems, whether in other courses or on the job.

## COMPONENTS OF UTC

UTC incorporates three types of modules.

### CONCEPT MODULES

Thirteen concept modules form the backbone of UTC (each presents a single concept in applied physics and discusses the application of that concept in each energy system):

1-0 Force.
2-0 Work.
3-0 Rate.
4-0 Momentum.
5-0 Resistance.
6-0 Power.
7-0 Potential and Kinetic Energy.
8-0 Force Transformers.
9-0 Energy Convertors.
10-0 Transducers.
11-0 Vibrations and Waves.
12-0 Time Constants.
13-0 Radiation.

### APPLICATION MODULES

Each of the 170 application modules discusses the application of a single physics concept in a single energy system, and each module includes a laboratory exercise in which students investigate the application. For example, 5E5 "Resistance of Wires" (located under Concept 5-0 "Resistance"), discusses the electrical resistance of wires. In the laboratory, students calculate and measure experimentally the resistance of various wires.

### SUPPLEMENTARY MODULES

In UTC, mathematics has been reduced to a minimum: one year of high school algebra is adequate preparation. The following eight supplementary modules are available for students requiring additional preparation or review:

S1 Formula Interpretation.
S2 International System of Units.
S3 Logarithms and Exponents.
S4 Angles and Triangles.
S5 Vectors and Scalars.
S6 Dimensional Analysis.
S7 Reading and Drawing Graphs.
S8 Precision, Accuracy, and Measurement.

## STRUCTURE OF A UTC MODULE

Each module in UTC contains seven basic elements:

**INTRODUCTION**

A brief description of the topics to be discussed, and their importance in technology, introduces each module.

**PREREQUISITES**

A list of prerequisite UTC modules, and notice of any special knowledge or skills required for successful completion of the module, are given.

**OBJECTIVES**

Specific tasks that a student should be able to accomplish after completing the module are stated in behavioral terms; objectives also are the basis of testing for UTC.

**DISCUSSION**

This segment is an explanation of the topic to be studied. It contains the appropriate physics as well as examples of its application. The discussion includes development of equations, example problems, figures and tables of useful data. It addresses each of the objectives (except those pertaining directly to a laboratory experiment).

**LABORATORY (called DEMONSTRATIONS in the Concept Modules)**

The laboratory section of UTC modules consists of the following three parts:

- "Materials." A list of all equipment and supplies required for the laboratory.
- "Procedure." A step-by-step set of instructions for performing the experiment.
- "Data." An organized format for recording all necessary data and observations.

**SELF CHECK**

A set of questions and problems based on the module objectives is included. It is intended for use by students to check their own understanding of module content.

**REFERENCES**

This list of sources directs students to additional information on topics discussed in the module.

TABLE OF CONTENTS


9-0 Energy Convertors
9F1 Turbines
9F2 Fluid Pumps
9F3 Wind Power
9F4 Fans and Blowers
9F5 Vacuum Pumps
9E1 Electric Generators
9E2 Alternators
9E3 Electric Motors
9E4 Solenoids and Relays
9E5 Photovoltaic Materials
9T1 Boilers
9T2 Thermoelectric Generators
9T3 Solar Collectors.

## INTRODUCTION

Our modern technological society depends upon the production, distribution, and consumption of large amounts of energy. These processes are made possible by a group of devices that can be classified as "energy convertors." These devices accept input energy in one energy system and deliver output energy in another system. Some of the input energy is lost, because energy convertors are not one-hundred percent efficient. This modules discusses (1) a variety of energy convertors, important in the conversion and application of energy and (2) the efficiency of individual energy convertors and systems.

## PREREQUISITES

Student should have completed Concept Module 6-0, "Power."

## OBJECTIVES

Upon completion of this module, the student should be able to:

- Describe energy convertors in general terms that apply to all energy conversion devices.
- Describe the operation of the following energy convertors:

  Vane pump.
  Electric generator.
  Turbine.
  Electric motor.
  Electric heater.
  Internal combustion engine.
  Boiler.
  Solar collector.

- Given two of the following quantities, determine the third:

  Input energy.
  Output energy.
  Efficiency.

- Given the efficiency of all the energy convertors used in an energy conversion system, determine the overall system efficiency.

## DISCUSSION

An energy convertor is a device that accepts energy input in one form and delivers energy in a different form at the output. For example, an electric fan actually is composed of two energy-converting devices. The electric motor converts electrical energy to rotational mechanical energy, and the fan blades convert this mechanical energy to the fluidal energy of moving air.

According to the "law of conservation of energy," energy neither can be created, nor destroyed. Thus, energy convertors actually do not create energy; they only change the input energy to another form. Another consequence of energy conservation is that all input energy must appear as output energy in one form or another. Some of this output energy always appears as heat energy because of resistance in the system. If heat energy is not the desired form of the output, it represents loss in the system. The efficiency of an energy convertor is given by Equation 1.

$$\eta = \frac{E_{out}}{E_{in}} (100) \qquad (1)$$

where

$\eta$ = efficiency.
$E_{in}$ = input energy.
$E_{out}$ = useful output energy.

Energy convertors also can be considered as power convertors, since some time always is involved in the energy-conversion process. In some cases, to discuss input and output powers is convenient, especially when energy convertors are in steady-state operation. Equation 2 states the relationship of energy, power, and time.

$$P = \frac{E}{t} \qquad (2)$$

where

P = power.
E = energy.
t = time.

A wide variety of energy-conversion devices are in common use today, and most energy used in the United States is changed in form several times before its final application. The electrical energy used to operate the fan mentioned earlier originally was chemical energy contained in a fuel. The fuel was burned to produce thermal energy, which was converted to fluidal energy in high-pressure steam. A turbine converted the steam to mechanical energy. Our entire society depends upon our ability to convert energy from one form to another in a controlled and efficient manner. Figure 1

is an energy-flow chart for the United States in 1975. Notice that 55% of the energy consumed in this country in 1975 was wasted. With increasing energy demands and decreasing supplies, the improvement of efficiency in energy convertors is of prime importance.

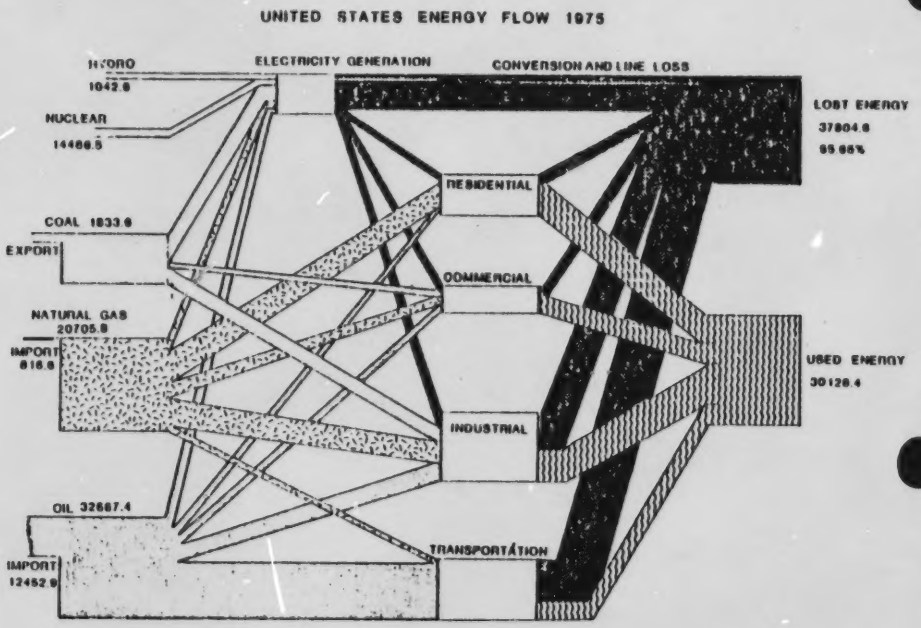



FIG. 1

Figure 2 is a chart showing the energy consumption in the United States during this century and the project supply and demand during the next century. This Figure shows the importance of improving energy convertors and of developing new types of energy convertors that can make efficient use of "ultimate energy sources.

Table I is a listing of the energy convertors discussed in the remainder of this module. Some of them have been in common use for many years, while others currently are in research and development. In this module, optical (radiant) energy is added as an additional and important form of energy. Energy convertors are discussed in the order of the form of their input energy.

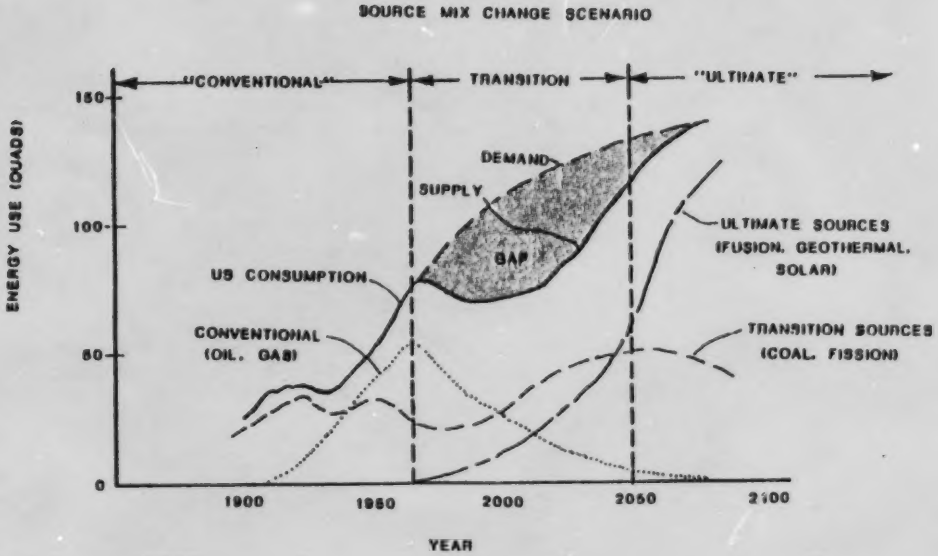



FIG. 2

TABLE 1. IMPORTANT ENERGY CONVERTORS

| INPUT ENERGY: Energy Convertors | OUTPUT ENERGY: Mechanical | Fluidal | Electrical | Thermal | Optical |
|---|---|---|---|---|---|
| Mechanical | | Pump Fan | Generator | | |
| Fluidal | Turbine Windmill | | Magneto-hydrodynamic Generator | | |
| Electrical | Motor | | | Heating Devices | Lighting Devices |
| Thermal | Combustion Engines | Steam Generator | Thermo-electric Generators | | |
| Optical | | | Solar Cells | Solar Collectors | |

## CONVERTORS OF MECHANICAL INPUT ENERGY

Mechanical energy is the energy of mass in motion and, as such, is one of the most important final forms of useful energy. However, mechanical energy also is an important intermediate step in several energy-conversion processes. Devices used to convert mechanical energy to other useful forms of energy are discussed below.

### FLUIDAL OUTPUT ENERGY

Figure 3 shows a vane pump used to convert mechanical rotational power to fluidal power. This type of pump can be used with either liquids or gases. The fluid is pulled into the inlet by the partial vacuum created as the vanes move upward from the inlet. The vanes are spring-loaded to maintain a seal against the pump housing. The fluid then is trapped between two vanes and forced through the pump to the outlet. This is only one possible pump configuration; there are several others. Figure 4 shows the characteristic curves of an axial piston pump. Notice that such pumps are highly efficient devices.

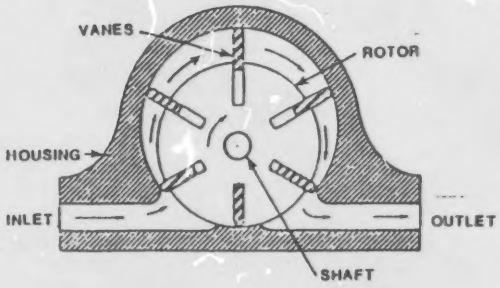



FIG. 3

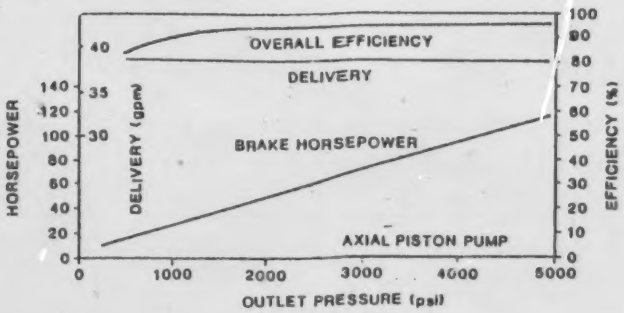



FIG. 4

Fans are devices used to convert mechanical input energy to the fluidal energy of moving air. Figure 5 shows a propeller fan and the air flow pattern produced. A centrifugal fan and its air flow are shown in Figure 6.

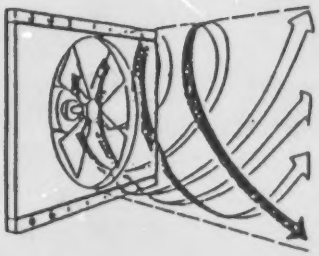


FIG. 5

## ELECTRICAL OUTPUT ENERGY

When an electrical conductor is passed through a magnetic field perpendicular to the field lines, a force is present on electrons in the conductor. This force causes them to flow, as shown in Figure 7a. Figure 7b shows this principle applied to an electrical generator. The loop of wire is rotated in a magnetic field by input mechanical energy. This energy is converted to electrical energy in the form of voltage and current in the loop. The electrical energy can be transmitted over long distances, to be converted to other forms of energy for application.

An alternator is a device in which the coils of wire are stationary, and a magnet is rotated inside them. Electrical generating plants produce electrical power using alternators in which the magnetic field is produced by a current flowing through rotating coils. These large alternators have an efficiency of 60-70 percent. The energy loss is caused by mechanical friction, air resistance, and electrical losses.

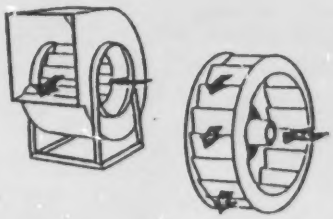


FIG. 6

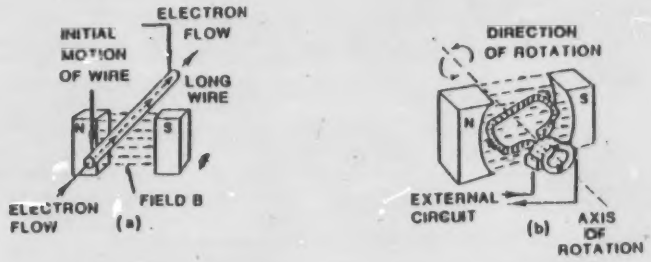



FIG. 7

## MECHANICAL OUTPUT ENERGY

Conversion of fluidal energy to mechanical energy is essential to the large-scale generation of electrical energy. All commercial electrical energy produced in the United States is fluidal energy at some point in its production. In most cases, this energy is contained in high-pressure steam. Figure 8 shows a section of a turbine used to convert this fluidal energy to rotational mechanical energy. Steam with high velocity and pressure strikes the movable blades of the turbine, exerting a force that causes the turbine to rotate. Several stages (additional sets of turbine blades) generally are used to extract more energy from the steam. The steam turbines used in modern electrical generation stations typically operate with efficiencies of 80-85 percent.

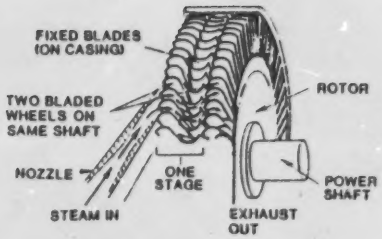



FIG. 8

Windmills also are devices for converting fluidal energy to mechanical energy, but they work with much lower fluid velocities than do most turbines. Many new designs for windmills have been developed and tested in recent years. The theoretical maximum efficiency of a windmill in changing the kinetic energy of moving air to rotational mechanical energy is 59 percent. The latest high-speed models are capable of actual efficiences of about 50 percent. Example A shows the calculation of windmill efficiency using Equation 1.

| EXAMPLE A: CALCULATING EFFICIENCY | |
|---|---|
| Given: | A windmill has a 25-foot diameter aluminum rotor; there is a wind velocity of 28 mi/h; and 20 kilowatts of electrical power is generated. |
| Find: | Efficiency (from mechanical energy input of wind to electrical-energy output). |
| Solution: | Convert to metric units. 25-foot diameter (d) becomes 762 cm; 28 mi/h velocity becomes 1252 cm/s; mass of air that moves through the circular area covered by the blades in one second must be calculated:<br><br>Blade area x air density x air velocity, or — |

$$m = \frac{\pi}{4} d^2 \rho v$$

where

- $m$ = mass of air that moves through area of blades.
- $d$ = diameter of rotor.
- $\rho$ = density of air (0.00129 g/cm$^3$).
- $v$ = wind velocity in cm/s.

The kinetic energy of this air is $1/2\ mv^2$. Thus, total energy brought by the wind to the blades in one second can be calculated as follows:

$$E_T = \left(\frac{1}{2}\right) \frac{\pi}{4} d^2 \rho v\ (v^2)$$

$$= 5.79 \times 10^{11} \text{ erg/s}$$

$$E_T = 5.79 \times 10^{4} \text{ joules/s}$$

(Remember: There are 30.48 cm in 1 foot, and 44.7 cm/s in mi/h.)

Electrical energy generated is 20,000 joules in one second (20 kW).

Efficiency: $\eta = \frac{E_{out}}{E_{in}} (100)$

$$= \frac{20,000}{37,900}$$

$$= 0.345$$

$$\eta = 34.5\%$$

(Remember: 1 joule = $10^7$ ergs.)

## ELECTRICAL OUTPUT ENERGY

A new kind of kinetic energy convertor, which may have practical importance for generation of electricity in the 1980's, is the magnetohydrodynamic generator. The design of this energy convertor is based upon the flow of hot, electrically-conductive gases through a magnetic field. These gases used are "plasmas"; that is, they consist of free electrons and positive ions.

There is a physical law that states, "The passage of such a gas through a magnetic field produces a voltage perpendicular to both the gas flow and the magnetic field." (Refer to Figure 9.)

The gas flows in a duct through a strong magnetic field, the field producing a voltage between two electrodes. Generation of electrical energy is accomplished by a cooling of the gas as it

expands in the duct. After cooling, the stream of gas is compressed, reheated, and returned to the generator.

A magnetohydrodynamic generator can operate with higher efficiencies than can a conventional electrical power plant. It has no moving parts; thus, its operation is more reliable than that of a conventional generator. Severe problems yet must be overcome, however. If they can be overcome, magnetohydrodynamic generators offer an important source of electrical energy.

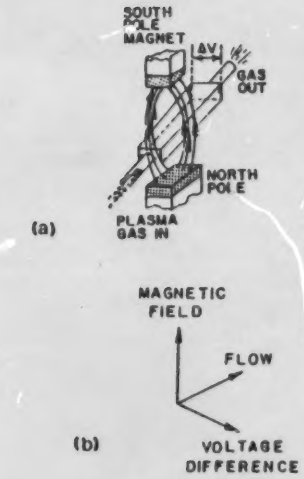



FIG. 9

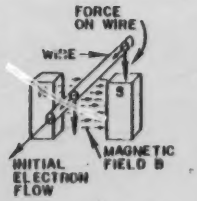



FIG. 10

## CONVERTORS OF ELECTRICAL INPUT ENERGY

### MECHANICAL OUTPUT ENERGY

In an electrical generator, a current is produced by the movement of a conductor through a magnetic field or by the movement of a magnetic field past a fixed conductor. In an electric motor, the forces that produce motion in conductors result from current flowing in the conductors perpendicular to a magnetic field, as illustrated in Figure 10. The basic construction of motors and generators is the same; in fact, many motors will operate well as generators if mechanical input energy is supplied.

Many types of electric motors have been developed for efficient operation in a variety of applications. Each motor operates at its maximum efficiency at the power for which it is designed. Figure 11 shows efficiency as a function of power delivered for a typical industrial motor.

Three important factors can conserve energy consumed by electric motors:

(1) A motor operates more efficiently at full, or near, capacity; that is, a motor just large enough to handle the load is much more efficient than a large one operating at far less than full capacity.

(2) External capacitors, mounted at the motor or at the distribution equip-

ment, can reduce power consumption of large a.c. motors.

(3) Synchronous motors consume less power than induction motors; therefore, their use can conserve energy. Some of them require both a.c. and d.c.; they operate at up to 1200 rpm and up to 300 hp. The initial cost for synchronous motors often is less than for induction motors.

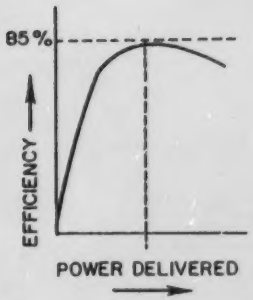



FIG. 11

## THERMAL OUTPUT ENERGY

A wide variety of common devices convert electrical energy to thermal energy. These devices include heaters, coffee pots, clothes dryers, industrial furnaces, and welders. In all cases, the thermal energy is produced by current flowing through a resistance. If the electrical load is a pure resistor, the conversion efficiency is 100 percent, and the thermal power can be calculated with Equation 3.

$$P = IV \qquad (3)$$

where

P = power (watts).
I = current (amperes).
V = potential difference (volts).

Example B shows the use of this equation in solving a problem.

**EXAMPLE B: THERMAL POWER OF A COFFEEPOT**

Given: A coffee pot operating at 110 V requires a current of 18.18 amperes.

Find: The thermal power of the coffee pot.

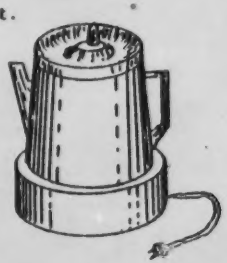
Solution: $P = IV$

$= (18.18\ A)\ (110\ V)$

$P = 2000\ W$

Converting to thermal units:

1 calorie = 4.186 joules



Thus, 1 cal/s = 4.186 W

$$P = (2000\ W)\left(\frac{1\ cal/s}{4.186\ W}\right)$$

$$P = 477\ cal/s$$

### OPTICAL OUTPUT ENERGY

An important application of electrical energy is in the production of light. Devices that convert electrical energy to optical energy include television sets, light-emitting diodes, and lasers, as well as both fluorescent and incandescent lights. Incandescent lights produce optical energy when tungsten wires within them are heated to high temperatures. A large portion of the energy they consume, therefore, is radiated as heat energy. Fluorescent lights do not depend upon thermal emission, and are much more efficient.

## CONVERTORS OF THERMAL INPUT ENERGY

### MECHANICAL OUTPUT ENERGY

Several types of heat engines have been developed for the conversion of thermal energy to mechanical energy. The most widely-used are the internal-combustion engines used in transportation. All these engines make use of an intermediate step in which thermal energy is changed to the fluidal energy of a gas and then to mechanical motion. Internal-combustion engines have an efficiency of about 30 percent.

### FLUIDAL OUTPUT ENERGY

Most of the energy consumed in the United States is produced initially in the form of hot combustion gases. Internal-combustion engines combine these gases and convert the resulting fluidal energy directly to mechanical energy. In other cases, such as in electrical power production, thermal energy is converted to fluidal energy in a boiler. Modern boilers consist of a maze of tubes filled with water and steam. These tubes are surrounded by the hot combustion gases, and thermal energy is conducted through their walls to the water inside. Every effort is made to extract as much thermal energy as possible from the hot gases. Figure 12 shows some of the design features of a modern boiler. The intake air for combustion and the input water to the boiler tubes are heated by escaping gas. A superheater at the output of the boiler increases both steam pressure and efficiency. Even with these innovations, boilers are only about 70 percent efficient.

### ELECTRICAL OUTPUT ENERGY

Thermoelectricity is the direct conversion of heat energy to electrical energy. When two different electrical conductors are joined, a small voltage is produced across the junction. The magnitude of this voltage depends upon the temperature of the junction. Figure 13 shows the schematic of a thermoelectric generator. The two junctions are at different temperatures ($T_1$ and $T_2$); therefore, the potential across the junction is not the same. This difference results in a net voltage across points A and B of the Figure. The voltage produced by thermoelectric generators is small, but large currents can be produced.

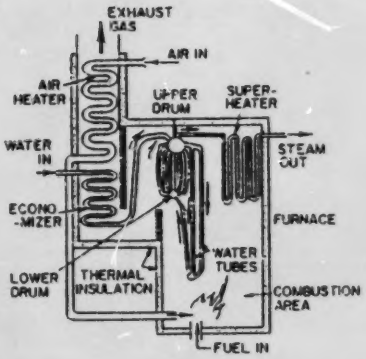



FIG. 12

Thermoelectric generators exhibit an efficiency of only about 10 percent and have the added disadvantage of high cost. Their only present application in this country, therefore, is in the production of electrical power for spacecraft.

## CONVERTORS OF OPTICAL INPUT ENERGY

### ELECTRICAL OUTPUT ENERGY

Photoelectric cells, often called "solar cells," are devices made of semiconductors, such as silicon, that directly convert a portion of the optical energy striking them into electrical energy. Solar cells have long been used to convert the energy of sunlight to electrical energy for use in satellites, but the cost of the devices and their low efficiency (typically less than 10 percent) has made large-scale use uneconomical.

FIG. 13

Example C illustrates the determination of the size of a photoelectric cell array for use in electrical power production for a satellite.

**EXAMPLE C: CALCULATION OF ELECTRICAL ENERGY USING SOLAR CELLS**

**Given:** Silicon photoelectric energy convertors are used on a satellite to generate electricity with 8% efficiency. The silicon photocells always are pointed directly at the sun. (Above the earth's atmosphere, the sun delivers 0.14 watts/$cm^2$ of light energy.)

**Find:** Area of solar cells needed to generate 12 watts of electrical energy.

**Solution:** Required watts = area x light energy x efficiency, or —

$$W = AE_L\eta$$

$$1200 \text{ watts} = (A \text{ cm}^2)(0.14 \text{ watts/cm}^2)(0.08)$$

$$A = \frac{12}{0.14 \times 0.08} \simeq 1.07 \times 10^3 \text{ cm}^2$$

$$A = 1070 \text{ cm}^2$$

## THERMAL OUTPUT ENERGY

Sunlight, streaming onto the earth's surface, represents a substantial source of energy. All one needs is a suitable "bucket" in which to catch it. Such buckets are under development. A solar house, with large windows facing south, collects solar energy and uses it directly as heat. Designs for solar water heaters have been under intensive development. Central solar-powered generating stations (large banks of movable mirrors track the sun and focus energy on a tower containing water) are being investigated. Solar-heated water is converted to steam used to drive a turbine to generate electricity.

# SUMMARY

Energy convertors are devices that convert energy from one energy system to another. In all cases except for the direct conversion of electrical energy to thermal energy, some of the input energy appears as waste heat. Thus, energy convertors are not 100 percent efficient. The accumulative losses in energy

convertors accounts for over half of all the energy consumed in the United States. Example D illustrates a major contribution to energy loss by showing the overall efficiency of a typical electrical generating station.

**EXAMPLE D: EFFICIENCY OF AN ELECTRICAL POWER PLANT**

**Given:** The following are the efficiencies of the energy convertors in a typical electrical power plant:

Boiler (chemical energy to thermal energy to fluidal energy) — 70%
Turbine (fluidal energy to mechanical energy) — 80%
Generator (mechanical energy to electrical energy) — 60%

**Find:** Overall efficiency.

**Solution:** The overall efficiency of a series of energy convertors is the product of the individual efficiencies expressed as decimal fractions:

$$\eta_T = \eta_1\eta_2\eta_3\ldots$$

Thus —

$$\eta_T = (0.70)(0.80)(0.60)$$
$$\eta_T = 0.336 = 33.6\%$$

This example illustrates the importance of improving the efficiency of energy convertors.

## EFFICIENCY OF AN ELECTRIC WATER PUMP

### MATERIALS

a.c. electric water pump.
Wattmeter.
Two large containers of known volume.
Connecting hose.
Stopwatch.

### PROCEDURE

This experiment requires energy calculations at both input and output of a combined electrical fluid system.

1. Arrange an electric pump to lift water from a reservoir on floor to a higher level as illustrated in Figure 14.

2. Connect wattmeter in pump circuit, as in Figure 15.

3. With a stopwatch, measure time necessary for pump to fill a relatively large container of known volume. Measure the electrical input power P and liquid head h. Record data in Data Table.

4. Complete Data Table, calculating energy input and useful energy output of system.

5. Calculate overall efficiency of system.

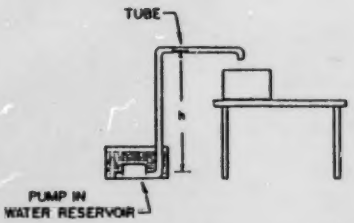



FIG. 14

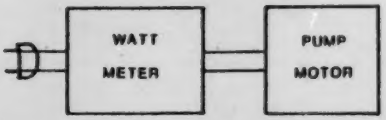



FIG. 15

| DATA TABLE | |
|---|---|
| Power Input (Electrical System) | Power Output (Fluid System) |
| Power input to pump P = _____<br>Time required to pump water<br>t = _____<br>Input energy Pt = _____ | Weight density of water<br>ρ = _____<br>Pressure head h = _____<br>Pressure p = ρh = _____<br>Volume of water pumped<br>ΔV = _____<br>Output energy for transferring water E = pΔV = ___ |
| Efficiency % = $\frac{\text{energy output}}{\text{energy input}}$ (100) = _____ | |

## EFFICIENCY OF A PHOTOCELL

### MATERIALS

Photocell (United Detector Technology model PIN-10DP or equivalent).
Microscope with calibrated reticle (not needed if area of photoconductor is known).
Milliammeter.
Resistor (50 Ω).
Wiring and clips for electrical connections.

### PROCEDURE

In this experiment, the efficiency of conversion of sunlight into electrical energy is measured. A photocell — a convertor of optical energy to electrical energy — is required. (Note: This experiment must be performed on a bright, clear day.)

1. Use microscope with calibrated reticle to measure area of photocell. (If area is known from manufacturer's specifications, this step can be omitted.)

2. Connect photocell, milliammeter A, and resistor $R_L$ as shown (Figure 16).

3. Point active area of photocell directly at sun; record value of current flowing through meter.

4. Calculate electrical energy ($E_{out}$) produced per unit time (power in watts). Use $E_{out} = I^2R_L$, where I is measured current (in amperes) and $R_L$ is resistance (in ohms).

5. Calculate optical energy per unit time (obtained from the known power per unit area delivered by sunlight to the earth's surface = 0.11 joule/s/cm$^2$); total energy per unit time (power in watts) is 0.11 x area of photocell (in cm$^2$).

6. Calculate efficiency $\eta$ of energy convertor: $\eta$ = electrical energy per unit time ÷ optical energy per unit time. $\eta$ = _____

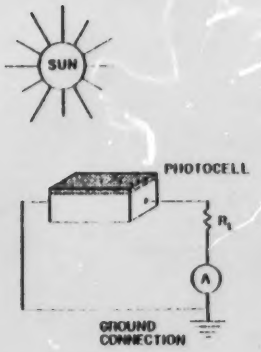



FIG. 16

## SELF CHECK

1. Describe the concept of energy convertors as it applies to all energy-conversion devices.

2. Identify and describe the operation of the energy convertor used to make the following conversions of energy:

   a. Electrical energy to thermal energy.
   b. Thermal energy to fluidal energy of steam.
   c. Optical energy to thermal energy.
   d. Fluidal energy to mechanical rotational energy.
   e. Electrical energy to mechanical energy.
   f. Mechanical energy to fluidal energy.
   g. Mechanical energy to electrical energy.
   h. Thermal energy to mechanical energy.

3. A 10-hp electric motor operates with an efficiency of 82%. Determine its electrical input power in kilowatts. (1 hp = 746 W.)

4. A solar-cell array received 750 J of radiant energy in 3 seconds and operates with an efficiency of 8.7%. Determine the average output power during this time interval.

5. A car with a mass of 1000 kg is raised through a height of 2 m by a hydraulic lift. The energy used originated as burning coal. The following energy convertors were used in the delivery of the necessary energy:

   Boiler – 75%
   Turbine – 82%
   Generator – 62%
   Electric motor – 79%
   Fluid pump – 93%
   Hydraulic cylinder – 96%

   Determine the overall efficiency of the system and the mass of the coal that must be burned initially to lift the car, if the energy content of the coal is 13,500 Btu/lb.

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UTC

UNIFIED TECHNICAL CONCEPTS

MODULE 9 F 1

TURBINES

# FLUID APPLICATION OF ENERGY CONVERTORS

Technical Education Research Center - Southwest

TERC - SW

## INTRODUCTION

The turbine, a prime mover in technology today, is a device that converts fluid energy into mechanical rotational energy. Gas turbine-powered automobiles and trucks are a reality, and gas-turbine turboprop engines are in daily use in aviation. Modern ocean liners are propelled by marine turbines. Various steam turbine-equipped generating plants (including nuclear plants) produce approximately 80% of the electricity in the United States. Water-powered turbines produce nearly 20% of America's electrical power.

In this module, the basic characteristics and operating principles of a turbine are presented. Energy transformations will be traced diagrammatically for gas, steam, wind and water turbines. In the laboratory the student will determine the efficiency of a small model water turbine.

## PREREQUISITES

Student should have completed Concept Module 9-0, "Energy Converters."

## OBJECTIVES

Upon completion of this module, the student should be able to:

- List two advantages of a turbine, compared to a reciprocating engine.
- Name and give the function of two major elements of a turbine.
- In one or two sentences, define the following terms:

  Impulse turbine.
  Reaction turbine.
  Staging.

- Calculate the input fluid power and efficiency of a turbine, given the input pressure, the volume flow rate and the output power.

- Given the appropriate equipment, calculate the input power, the output power and the efficiency of a model water turbine.

## DISCUSSION

Energy conversions occur through a device called an energy converter. A source of energy is provided to the converter in initial form. As the energy passes through the converter, it is converted to a desired output form of energy, as shown in Figure 1. Unfortunately, some of the input energy is also converted to a waste form of energy such as heat, which represents a loss of useable energy in the conversion process.

A well-known energy converter is the turbine, which consists of two major elements, a high-energy working fluid and a rotor. The input energy to the turbine is provided by the high-energy fluid (combustion gases, steam, wind or a flowing fluid such as water). The flowing medium has an initial high energy content as it enters the turbine. It flows through the turbine and causes the rotor to spin. The rotor, in effect, extracts energy from the moving fluid and converts the extracted fluid energy to a mechanical rotational form. The mechanical rotational energy is transmitted along the rotor shaft where it is available as useful output energy. These elements of a turbine operation and energy flow are illustrated in Figure 2.

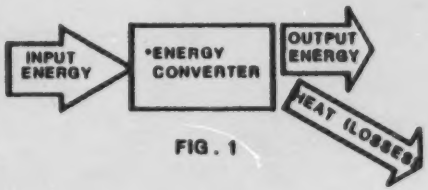


FIG. 1

The efficiency of an energy transformer is given by Equation 1.

$$\eta = \frac{E_{out}}{E_{in}} (100) \qquad (1)$$

where

$\eta$ = % efficiency.
$E_{in}$ = energy input.
$E_{out}$ = energy output.

Since output energy and input energy are developed and used over the same time interval, an alternate form of Equation 1 is given by Equation 2.

$$\eta = \frac{P_{out}}{P_{in}} (100) \qquad (2)$$

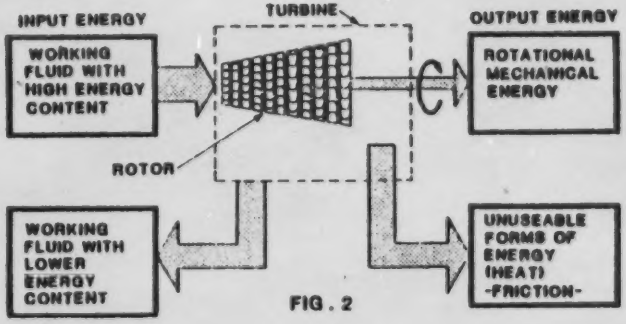


FIG. 2

where

$P_{in}$ = power input.

$P_{out}$ = power output.

Equation 2 is used to find efficiency in Example A. High efficiency is one of the distinct advantages of a turbine over reciprocating engines since the latter wastes much energy starting and stopping heavy pistons. (See Example A.) Turbines are designed to rotate smoothly at high rpm with little vibration and no change in direction of the rotor. Since there is little vibration, turbines also may be lighter in weight than other engines.

**EXAMPLE A: EFFICIENCY CALCULATIONS**

**Given:** A marine turbine which develops 55,000 horsepower at the rotor shaft and requires an input power of 55,555 horsepower.

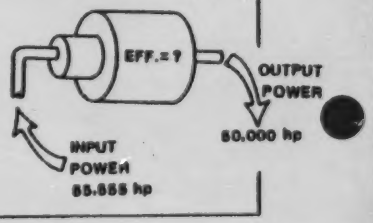
**Find:** The % efficiency.

**Solution:**

$$\eta = \frac{P_{out}}{P_{in}} \quad (100)$$

$$= \frac{(50{,}000\ \text{hp})}{(55{,}555\ \text{hp})} \quad (100)$$

$$\eta = 90\%.$$




The modern water turbines used in generating electricity convert the available potential heat energy of water into electrical energy at efficiencies as high as 94%. Some of these units develop as much as 700,000 horsepower. The efficiency of steam turbines can be improved if the rotor is constructed with series of axial stages having alternate rows of rotating and fixed blades, as shown in Figure 3. Each stage extracts energy from the fluid flowing into it from the previous stage. Turbines of this type are known as impulse-reaction turbines. The term "impulse" refers to the process by which the available heat energy in steam is transformed into kinetic energy as the steam jet flows from the nozzles. This kinetic energy is transformed to work done on the rotor by impinging on a rotating row of blades. In pure impulse turbines, such as some water turbines, the working fluid undergoes little pressure change passing through a stage. The term "reaction" turbine is applied to the type of turbine which derives an additional thrust by directing the working fluid through a curved blade, thereby changing the

fluid's direction. An additional thrust is gained from the change in momentum of the working fluid. Most actual turbines are a combination of impulse and reaction principles. Practical turbine systems for converting fluid energy to mechanical energy in electrical generating plants often consist of two or three turbines mounted on the same shaft. Thus, the exhaust steam from a high-pressure turbine may be used to power another turbine designed for lower pressure operation.

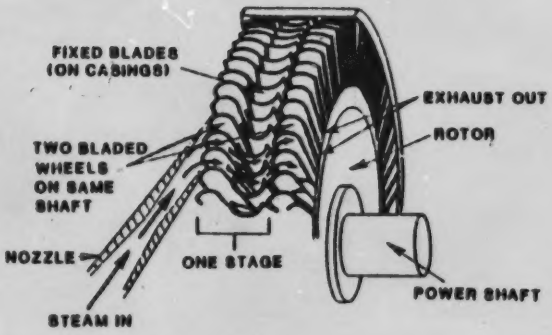



FIG. 3

## MODEL WATER TURBINE

### IMPULSE-REACTION TURBINE

Figure 4 shows the variables that must be measured in order to calculate the input power to a water turbine. The input power to the water turbine is given by Equation 3.

$$P_{in} = p\frac{V}{t} \qquad (3)$$

where

$P_{in}$ = power input.
$p$ = pressure.
$V$ = volume.
$t$ = time.

The use of Equation 3 is illustrated in Example B.

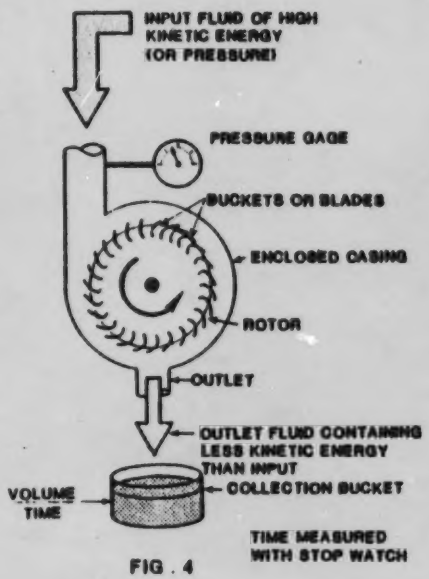



FIG. 4

**EXAMPLE B: CALCULATION OF INPUT POWER**

**Given:** A water turbine in which the pressure of the incoming fluid is 50 lb/in$^2$ and the volume of water collected is 0.25 cubic feet (roughly 2 gal.) in a 2-minute period of time.

**Find:** (a) Calculate the input power, and express the answer in horsepower.

(b) Convert the given data to metric units, and calculate the input power in watts.

**Solution:**

$$p = \text{pressure} = 50 \frac{\text{lb}}{\text{in}^2} \left(\frac{6895 \text{ N/m}^2}{1 \text{ lb/in}^2}\right) = 344{,}750 \frac{\text{N}}{\text{m}^2}$$

$$V = \text{volume} = 0.25 \text{ ft}^3 \left(\frac{1 \text{ m}^3}{35.315 \text{ ft}^3}\right) = 0.0071 \text{ m}^3$$

$$t = \text{time} = 2 \text{ min} \left(\frac{60 \text{ s}}{1 \text{ min}}\right) = 120 \text{ s}$$

(a) English System:

$$P_{in} = p \frac{V}{t}$$

$$= \left(50 \frac{\text{lb}}{\text{in}^2}\right) \left(\frac{144 \text{ in}^2}{1 \text{ ft}^2}\right) \left(\frac{0.25 \text{ ft}^3}{120 \text{ s}}\right) = \frac{15 \text{ ft·lb}}{\text{s}}$$

$$= \frac{15 \frac{\text{ft·lb}}{\text{s}}}{\left(\frac{550 \frac{\text{ft·lb}}{\text{s}}}{1 \text{ hp}}\right)} \qquad \left(\text{Recall: } 550 \frac{\text{ft·lb}}{\text{s}} = 1 \text{ hp}\right)$$

$$P_{in} = 0.027 \text{ hp}$$

(b) Metric System:

$$P_{in} = p \frac{V}{t}$$

$$= \left(344{,}750 \frac{\text{N}}{\text{m}^2}\right) \left(\frac{0.0071 \text{ m}^3}{120 \text{ s}}\right)$$

$$P_{in} = 20.4 \text{ watts}$$

Note: Metric units are more appropriate for power measurements of small laboratory water turbines. A useful conversion is 1 hp = 746 watts.

## OUTPUT POWER OF A LABORATORY WATER TURBINE

The output power from the laboratory water turbine is available at the rotating shaft in the form of mechanical rotational, kinetic energy per unit time. The amount of output power will be less than the input power because of losses in the energy transformation process. In order to measure mechanical rotational power, another energy transformation is used. A device called a prony brake is constructred in such a manner that when applied to the rotating shaft, a frictional force (a braking load) is applied to the shaft; and the available power is converted to dissipated power in the form of heat developed per unit time and any remaining mechanical rotational power. This power transformation is illustrated by Equation 4.

FROM THE TURBINE | AT THE PRONY BRAKE

[Available mechanical rotational power] = [braking load power, less loss in form of heat] + [remaining mechanical rotational power at the shaft] + [other losses] (4)

No load condition.

Evidenced by remaining rpm at the shaft.

When the prony brake is adjusted in order that the turbine almost stalls (the output shaft ceases to rotate), then all the available mechanical rotational, kinetic power from the water turbine would be converted to braking load power (plus other, hopefully negligible, losses).

The prony brake consists of a friction belt that wraps around a smooth drum attached to the output shaft of the water turbine. The ends of the belt are attached to spring scales, as shown in Figure 5. The braking load (frictional force) applied at the surface of the drum is the difference in the spring scale readings ($F_1 - F_2$). A mechanical revolution counter attached to the rotating shaft enables revolutions per unit time to be determined.

Braking load power is given by Equation 5.

$$P_{load} = (F_1 - F_2)\,\frac{\pi dN}{t} \qquad (5)$$

where

$P_{load}$ = breaking load power.
$F_1$ = highest spring scale reading.
$F_2$ = lowest spring scale reading.

$\pi$ = 3.14.
d = drum diameter.
N = number of revolutions.
t = time in seconds for N revolutions.

Equation 5 is used to solve a problem in Example C.

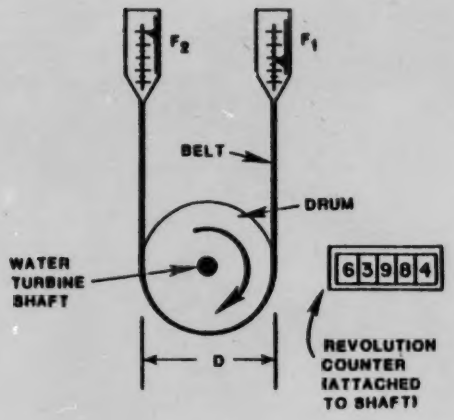



FIG .5

**EXAMPLE C: CALCULATION OF BRAKING LOAD POWER**

Given: A prony brake turns 180 revolutions in 3 minutes when the spring scale readings are 15.68 N and 0.98 N respectively and the diameter of the friction drum is 8 cm.

Find: The braking load power (in watts) developed.

Solution: From Equation 5:

$$P_{load} = (F_1 - F_2)\,\frac{\pi d N}{t}$$

$$= (15.68 - 0.98)\ N \quad (3.14) \quad (0.08\ m)\left(\frac{180\ rev}{180\ s}\right)$$

$$P_{load} = 3.69\ watts$$

Efficiency of a laboratory turbine is calculated in Example D. It is low compared to the 94% efficiency possible with some large turbines. The laboratory turbine is a single-stage unit that extracts only a small percentage of the power flowing through it.

**EXAMPLE D: CALCULATION OF EFFICIENCY**

Given: A laboratory water turbine with power input of 20.4 watts and braking power output of 3.69 watts.

Find: % efficiency.

Solution:

$$\eta = \frac{P_{out}}{P_{in}} \quad (100)$$

$$= \frac{(3.69 \text{ watts})}{(20.4 \text{ watts})} \quad (100)$$

$$\eta = 18\%$$

## SUMMARY

The turbine converts fluid energy into mechanical rotational energy. It is one of the more efficienct devices available, and is used as a power source for trucks, ships, aircraft, electrical power plants, and other equipment. The major sources of input energy to the turbine are gas, steam, wind or water.

## EFFICIENCY OF A WATER TURBINE

### MATERIALS

Water turbine, equipped with pressure gage, 0 to 60 psi.
Prony brake with scales and mechanical revolution counter.
(Available from Central Scientific Company or equal supplier.)
A two-gallon catch bucket.
Stopwatch.
Sink.

### PROCEDURE

The model water turbine used for this laboratory experiment develops such small power that calculations should be done in the metric system of units and measurements. The reason for this suggestion are indicated by the results of Example B. Data Table I should be completed using both the English and the metric systems.

1. Arrange the water turbine and its associated equipment in the manner shown in Figure 6. Note: Some of this procedure requires two persons.

2. Check system for leaks, since a 30 $lb/in^2$ to 60 $lb/in^2$ pressure is required.

3. Arrange catch bucket in such a manner as to allow it to catch all water that passes through turbine in a time measured with stopwatch.

4. Shut off water, and dry catch bucket. Move catch bucket out of way of exit tube.

5. Measure diameter of output pulley drum, and record this data in Data Table I.

6. Adjust position of prony brake scales to produce a small tension in brake band. (The scale readings will normally be the same with turbine stopped.)

7. Turn on water supply to turbine, and record water pressure in Data Table I, Trial I.

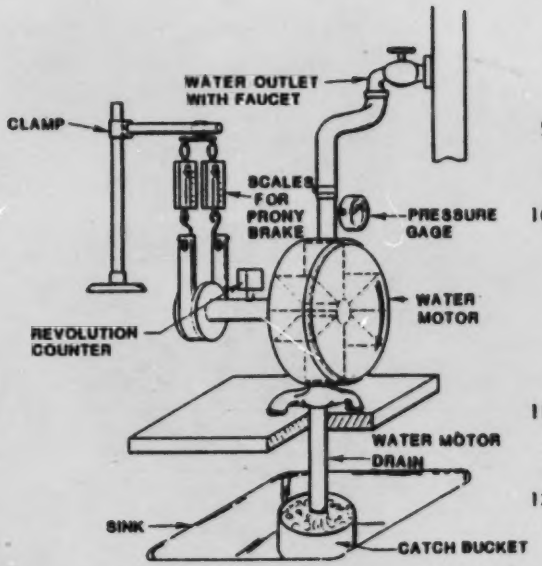



FIG. 8

8. Simultaneously start the stopwatch, slide catch bucket underneath exit tube, and engage mechanical revolution counter at output side of turbine. In a measured time, catch as much water in catch bucket as can be handled reasonably without spilling.

9. During trial, record prony brake scale readings, $F_1$ and $F_2$ in Data Table 1.

10. Simultaneously, stop stopwatch, remove catch bucket from underneath exit tube and disengage the mechanical revolution counter. Record in Data Table 1 number of revolutions indicated by counter during trial and time interval shown on stopwatch.

11. Measure volume of water collected during trial, and record in Data Table 1.

12. Repeat steps 7 through 11 for increasing tensions in prony brake band. Perform at least 6 more trials with increasing tensions in brake band, ending with a trial in which turbine is almost stalled by braking load placed on it.

13. Convert the collected data in Data Table 1 to metric units and record the values in the indicated columns of Data Table 1. (Table 1 gives metric conversion factors.)

14. Using data taken from Data Table 1, calculate input power to turbine in watts for trials 1 through 7 of the experiment; record in Data Table 2.

15. Using data taken from Data Table 1, calculate output power from turbine in watts for trials of the experiment, and record in Data Table 2.

16. Calculate and record % efficiency for each trial, using Equation 2:

$$\eta = \frac{P_{out}}{P_{in}} (100)$$

17. Calculate revolutions per second and braking load for each trial. Record in Data Table 2.

18. Why would a multi-stage turbine be more efficient than this single-stage turbine, even when the inlet water pressure and flow rate are the same?

| DATA TABLE 1 | | | | | | | |
|---|---|---|---|---|---|---|---|
| WATER TURBINE | | | | | | | |
| TRIAL | WATER PRESSURE (GAGE) $lb/in^2$ | $n/m^2$ | $F_1$ lb N | $F_2$ lb N | REVOLUTIONS N | TIME INTERVAL t(s) | VOLUME OF WATER $(m^3/s)$ |
| 1 | | | | | | | |
| 2 | | | | | | | |
| 3 | | | | | | | |
| 4 | | | | | | | |
| 5 | | | | | | | |
| 6 | | | | | | | |
| 7 | | | | | | | |
| Diameter of pulley drum: _____ meters. | | | | | | | |

| TABLE 1 | |
|---|---|
| CONVERSION FACTORS FOR METRIC UNITS | |
| 1 lb = 4.448 N, | 1 m = 39.37 In |
| 1 $\frac{lb}{in^2}$ = 6.895 KPa, = 6895 $\frac{N}{m^2}$. | 1 $m^3$ = 35.315 ft |

| DATA TABLE 2 | | | | | |
|---|---|---|---|---|---|
| TRIAL | POWER INPUT (WATTS) | POWER OUTPUT (WATTS) | EFFICIENCY | REVOLUTION PER s | BRAKING LOAD ($F_1 - F_2$) (NEWTONS) |
| 1 | | | | | |
| 2 | | | | | |
| 3 | | | | | |
| 4 | | | | | |
| 5 | | | | | |
| 6 | | | | | |
| 7 | | | | | |

## SELF CHECK

1. Describe two characteristics of turbines that result in advantages over internal combustion engines.

2. Name and give the function of the two major elements of a turbine.

3. Describe the differences between an impulse turbine and a reaction turbine.

4. Describe staging in an impulse-reaction turbine.

5. A turbine has an input pressure of 100 psi, a flow rate of 400 $ft^3$ per minute and an efficiency of 75%. Calculate the input power and output power of the turbine in horsepower and kilowatts.

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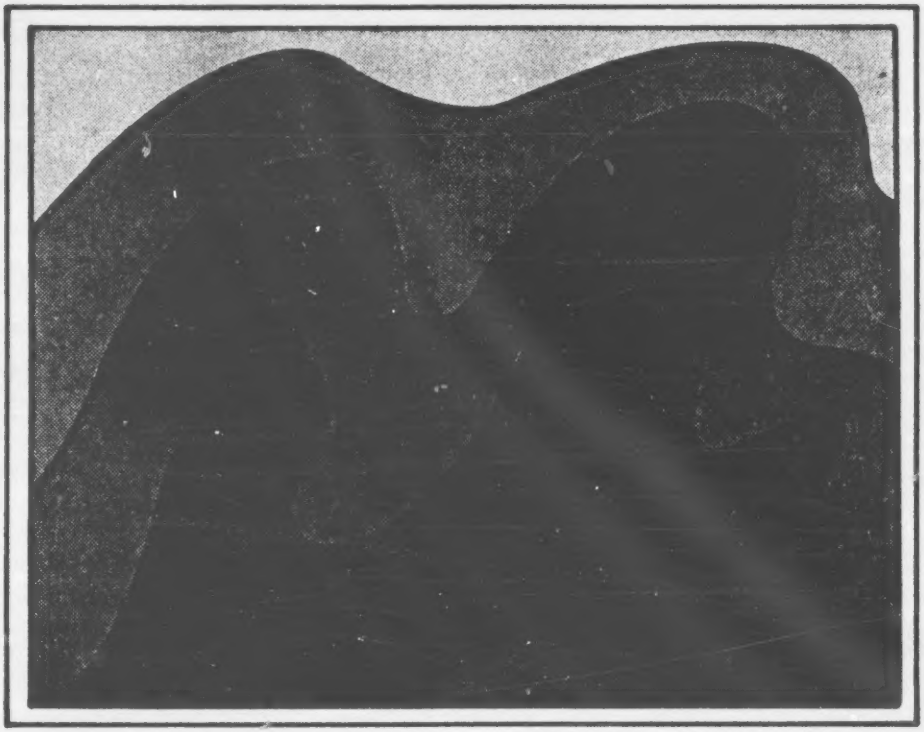
UTC

UNIFIED TECHNICAL CONCEPTS

MODULE 9 F 2

FLUID PUMPS



FLUID APPLICATION OF ENERGY CONVERTORS

Technical Education Research Center - Southwest TERC - SW

## INTRODUCTION

Fluid pumps are energy converters that transform mechanical energy into fluid energy. Fluid energy supplied by pumps is utilized either to circulate fluid or to pressurize it for use in hydraulic fluid motors or cylinders. Fluid pumps may be classified by a number of characteristics, but the most fundamental is displacement. The non-positive displacement, or hydrodynamic, pump is usually of the centrifugal type and is used to move large volumes of fluid at low pressures. Positive displacement pumps produce high pressure because the fluid in them is propelled by tightly-fitted mechanical components such as gears, vanes, or pistons.

This module discusses the principles, characteristics, and applications of the hydrodynamic pump and several types of positive displacement pumps. In the laboratory, the student will examine the characteristics of a hydrodynamic pump.

## PREREQUISITES

Student should have completed Concept Module 9-0, "Energy Converters," and Application Module 6F1, "Hydraulic Power."

## OBJECTIVES

Upon completion of this module, the student should be able to:

- State four characteristic differences between hydrodynamic pumps and positive displacement pumps.
- State the most common application of the hydrodynamic pump.
- State the most common application of the positive displacement pump.
- Draw and label diagrams of the following types of pumps; show direction of motion for moving parts and direction of

Fluid flow:

Centrifugal.
External gear.
Unbalanced vane.
Axial piston.

- Explain with the use of diagrams how unbalanced vane pumps and radial and axial piston pumps can be used as variable volume pumps.

- Given the appropriate equipment, make the necessary measurements, and draw the pump characteristic curves for a centrifugal pump.

## PUMP PRINCIPLES

Fluid pumps are energy converters that transform mechanical energy from a motor into fluid energy. Mechanical force is exerted at the outlet by a motor, causing a partial vacuum at the inlet, as demonstrated by the piston pump in Figure 1. When the piston (1) is moved by mechanical force to the left, a partial vacuum is created in the chamber (4). The drop in pressure closes the outlet check valve (3) and opens the inlet check valve (2), permitting fluid to fill the chamber. As the piston moves to the right, the pressure it exerts upon the fluid causes the inlet check valve (2) to close and the outlet check valve (3) to open and thereby to allow flow at the outlet.

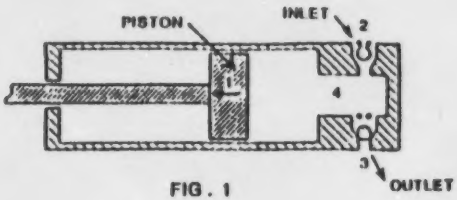


FIG. 1

A potential danger in pumps is "cavitation," which refers to the "cavity" of gases produced when the pressure at the inlet of the pump is so low that fluid vaporizes. Such vapor is carried by the pump through the outlet, where it rapidly compresses under pressure, causing shock waves so powerful that pump components can be damaged. Auxiliary pumps often are used to increase inlet pressure.

## THE NON-POSITIVE DISPLACEMENT (HYDRODYNAMIC) PUMP

The centrifugal pump, illustrated in Figure 2, is the most common hydrodynamic type. The principle behind this pump is centrifugal force produced when an object is forced in a circular motion. The object tends to move in a straight line away from the center of the circle. In the centrifugal pump, fluid enters the inlet at the center of the pump into a rotating, finned impeller that spins the fluid so rapidly that it moves, in a straight line, through the outlet. (Centrifugal force is not to be confused with centripetal force, or "force pulling toward the center.")

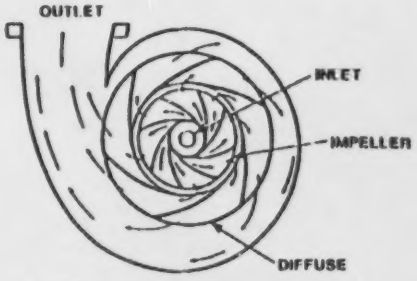


FIG. 2

There is always some "slippage" within the centrifugal pump. Slippage is the fluid not forced through the outlet of the pump although contacted by the pump com-

ponents. Even at a constant speed the centrifugal pump does not always displace, or move, the same amount of fluid, because the amount of suction head and pressure head determine how much fluid will be moved by the pump. "Suction head" is the amount of pressure the pump must exert upon a fluid of a given density to raise it a given height to the pump. "Pressure head" is the back pressure caused by the equivalent height against which the fluid must be pumped, or the resistance of the load.

When head pressure is great, slippage will be greater and displacement less. Even if the outlet of a centrifugal pump is blocked, slippage prevents damage to pump components. The pump displayed in Figure 2 is an improved design with a diffuser that reduces slippage and increases efficiency. The centrifugal pump produces low pressure but high volumes. It must be primed with fluid before it will start; that is, it must contain enough fluid within its housing to begin pumping action.

A characteristics graph, similar to that given in Figure 3, often is used to determine the size of centrifugal pump required for a given job. Pump size depends upon volume of fluid to be moved, time required to move it, suction and head pressure to be overcome, motor horsepower, and pump efficiency. Three characteristics for a centrifugal pump are plotted against volume flow rate, which is represented in gallons per minute at the bottom of the graph. Notice that each curve is associated with different vertical scales. Delivery pressure, represented by the top curve, drops as the flow rate increases. Overall efficiency rises to a maximum and then drops. Brake horsepower requirement for the pump motor increases as the total head and flow rate increase. Example A illustrates the use of a pump characteristic graph in plotting flow rate and efficiency.

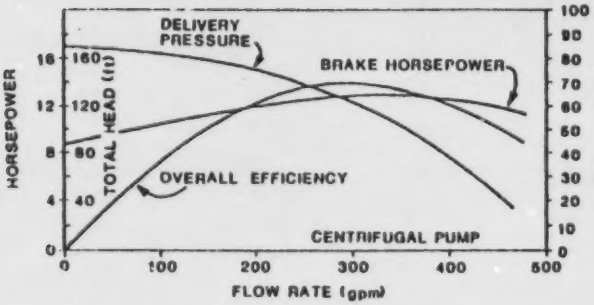
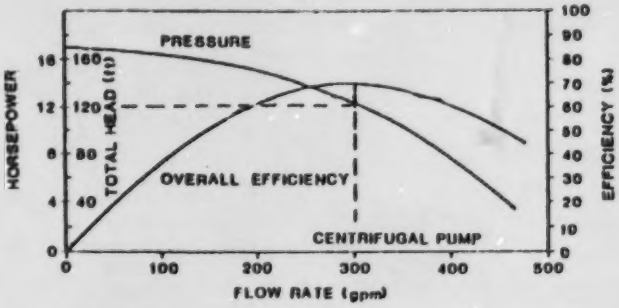



FIG. 3

| EXAMPLE A: USE OF PUMP CHARACTERISTICS GRAPH | |
|---|---|
| Given: | The below graph is for a particular pump. |
| Find: | The flow rate and % Efficiency of this pump when there is a total head of 120 ft. |
| Solution: | Locate total head in left vertical column. Extend |

line to right until it intersects Pressure curve, and draw line, at 90°, to horizontal axis (flow rate), which gives a flow rate of approximately 310 gallons per minute. Extend vertical line upward until it intersects the overall efficiency curve. From this intersection, draw horizontal line to right margin, which is the % Efficiency line. In this case the efficiency is 70% (peak).




The most frequent application of the centrifugal pump is the circulation of large volumes of fluid at low pressure. Applications include use in automobile water pumps and lubricating pumps for machinery and shop processes.

## POSITIVE DISPLACEMENT PUMPS

The term "positive displacement" means that a specific volume of fluid is moved, or displaced, each time the pump makes a revolution, regardless of pump speed. There is little slippage in this kind of pump, because the fluid is moved by tightly-fitted components, such as gears, vanes, or pistons. Greater pressures, but lower volumes, are achieved than with the centrifugal pump. If the outlet is blocked, pump damage will result, unless safety valves are built into the system. No priming is required because of little slippage. Hydraulics is the most common application of the positive displacement pump.

Positive displacement pumps are classified also by delivery and motion. Delivery of a fluid by a pump may be either constant of variable. The constant-delivery pump displaces the same amount of fluid in a given time at the same speed. Fluid from the constant-delivery pump drives machines not requiring a speed change. The variable-delivery pump contains design features that enable its output volme to be changed manually or automatically without

changing the speed of the power source. Variable-delivery pumps are used in such applications as conveyor systems, continuous-processing equipment, and constant-tension devices, in which variable delivery fluid rate is necessary.

Motion is either rotary or reciprocating. Rotary pumps utilize components that move in a circular direction. Reciprocating pumps contain pistons that move backwards and forwards, as was shown earlier in Figure 1.

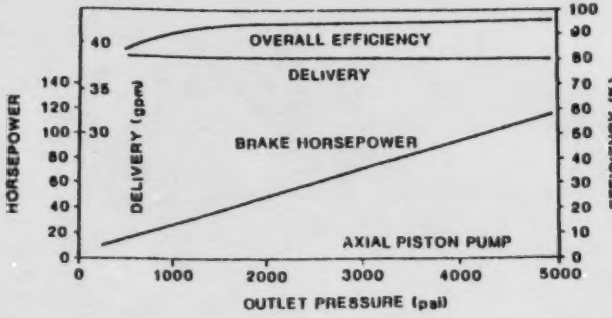



FIG. 4

Figure 4 consists of pump characteristics for use with positive displacement pumps. In this case, pump outlet pressure in psi, is represented at the lower part of the graph. Since there is almost no slippage, the delivery flow rate is constant at all pressures. Overall efficiency rises from about 80% at very low pressure (for example, at 100 psi) to over 95% from 1000 psi to capacity. The only characteristic that changes significantly is that for required brake hp, which increases linearly with pressure.

## TYPES OF POSITIVE DISPLACEMENT PUMPS

The three types of positive displacement pumps are (1) gear, (2) vane, and (3) piston.

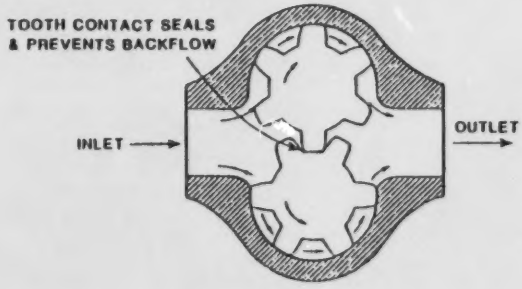



FIG. 5

### GEAR PUMPS

Figure 5 illustrates an external gear pump. Both external gears (spur gears) have teeth around their outside surfaces. One is a motor-driven gear, which in turn drives the second gear, causing a tight seal to exist between the meshing teeth to prevent slippage. Both gears are fitted tightly into a housing. As the grooves in the gears collect fluid at the inlet and rotate, the fluid is sealed in the grooves as the spurs contact the housing. The gears rotate to the outlet side of the housing, where they release their fluid.

Internal gear pumps have one large, internal, ring gear with teeth on its inside surface, as in Figure 6. An external gear (with teeth on its external surface) fits inside, its teeth fitting closely into the internal gear teeth on one side (top left side in drawing). Fluid is drawn into the grooves of both moving gears at the inlet as the outer gear ceases contact with the inner in that area. Fluid is held in the grooves by a stationary crescent until both gears rotate to the outlet, where the external teeth again contact the inner, forcing the fluid through the outlet. Internal gear pumps are capable of greater pressures than external ones.

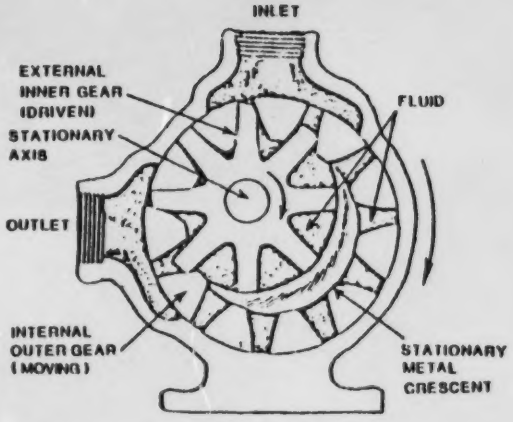


FIG. 6

Similar to the external gear pump is the lobe pump (Figure 7). Both lobe elements are driven externally but do not actually make contact, which causes less wear but more slippage. The lobe pump has a large volume output per revolution.

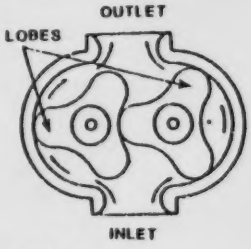


FIG. 7

## VANE PUMPS

Vane pumps are either unbalanced (with variable or unvariable volume capacity) or balanced. As indicated in Figure 8, the unbalanced vane pump of the unvariable type consists of a circular rotor containing radial sliding vanes held against the housing by spring pressure behind each vane and by the rotary motion. Because the rotor is unbalanced (off center) in the housing, fluid is trapped at the inlet between the housing and the vanes, as in the grooves of a gear pump. As the rotating vanes deliver fluid to the outlet, they are pushed inward by the housing, causing the fluid to be compressed between the rotor and the housing and to flow through the outlet. The vane pump is used on machine tools because of its reliability and low initial cost.

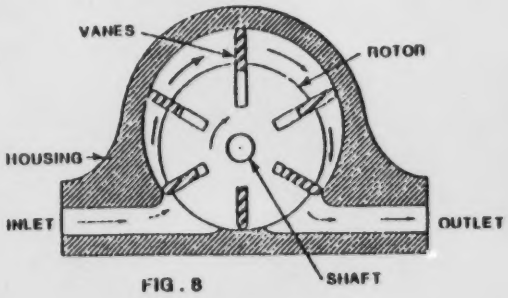


FIG. 8

Figure 9 demonstrates an unbalanced vane pump whose output can be varied externally when the position of either of the two movable

cylinder casings is changed. Fluid flow is reversible by movement of the casings.

The balanced vane pump (Figure 10) is not capable of variable-volume output, although its design reduces bearing pressure and wear found in the unbalanced type. The balanced vane pump is designed with two outlets and two inlets. It contains two opposite areas of equal fluid movement, balanced on opposite sides of the housing.

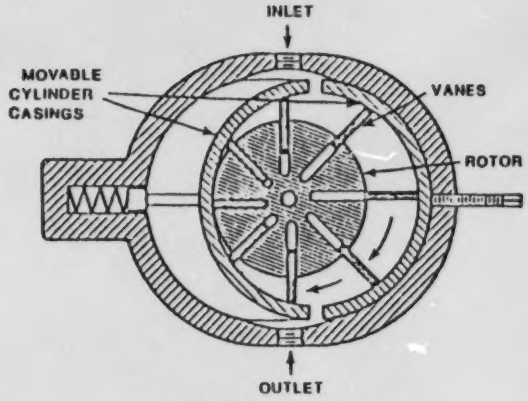



FIG. 9

## PISTON PUMPS

Both radial and axial piston pumps contain reciprocating pistons. Figure 11 displays a radial piston pump, termed "radial" because piston motion is along a radius. The rotor is off center, or unbalanced, as in the unbalanced vane pump. However, instead of fluid being carried in a circular motion between vanes, it is forced into circular pistons as they move outward from the rotor against the housing casing. Springs and rotary motion cause the pistons to press against the casing. When the rotor containing the pistons rotates against the unbalanced casing, the pistons are forced inward and

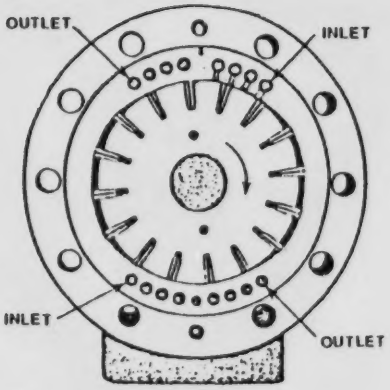



FIG. 10

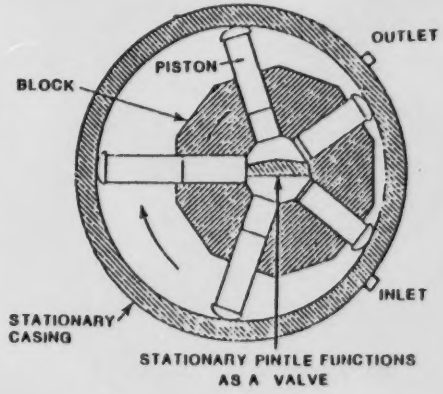



FIG. 11

outward; and the fluid in them passes through a stationary pintle that is open just at the instant when the fluid is forced through at the center of the rotor. Most radial pumps have the variable-volume capacitymade possible by movable casings.

Axial piston pumps operate upon the principle shown in Figure 12. These pumps are called "axial" because the piston cylinder block is varied from parallel to the axis of the drive shaft to several degrees out of parallel, where flow is the greatest. The cylinder block and thrust plate rotate together, as indicated by Figure 13. When the pistons move away from center, they are filled with fluid from one side of the pintle. When they compress toward the center, they expel fluid at the outlet on the other side. The axial piston pump is the most popular piston pump, since it is more compact and less complex than the radial type.

The most common use of positive displacement pumps is in hydraulics, where they are used to pressurize hydraulic fluid.

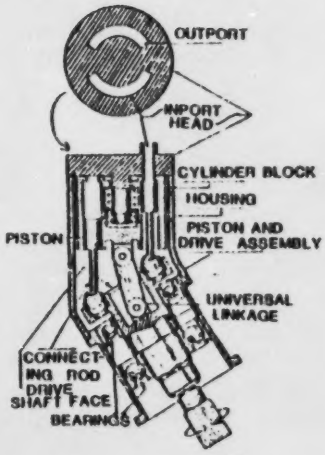



FIG. 12

## SUMMARY

Fluid pumps convert mechanical energy into fluid energy, and are used to circulate or to pressurize fluid. Hydrodynamic pumps are used primarily to circulate fluids. Positive displacement pumps are used in pressure applications often required in hydraulic systems. The four characteristic differences between these two pump types are defined in Table I.

Pump characteristic curves usually are furnished by pump manufacturers for each size pump. These curves are used to determine the size, or capacity, of pumps required for given applications.

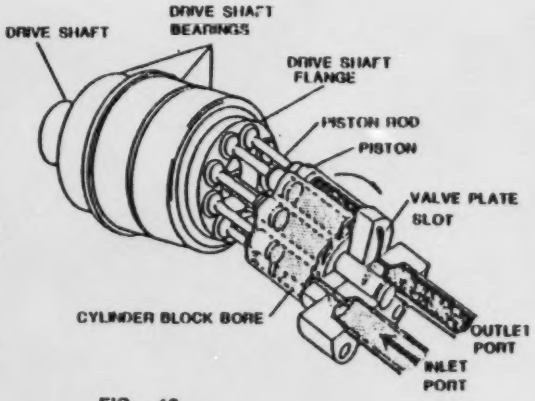



FIG. 13

| TABLE 1. CHARACTERISTIC DIFFERENCES BETWEEN HYDRODYNAMIC AND POSITIVE DISPLACEMENT PUMPS | | |
|---|---|---|
| Characteristic | Hydrodynamic | Positive Displacement |
| Pressure | Low | High |
| Volume Flow Rate | High and variable | Low and constant |
| Priming | Required | Not required |
| Danger of blocked output | Slippage prevents damage | Damage to pump |

## PREPARATION OF PUMP CHARACTERISTICS CURVE

### MATERIALS

Small vertical a.c. centrifugal pump with output of approximately 5 gal per min.
Two water containers: one for pump at approximately 5 gal capacity and one for use as receptacle at approximately 2 gal capacity, marked at 1 gal point.
a.c. Wattmeter.
Laboratory timer.
Yardstick or tape measure.

### PROCEDURE

1. Connect pump, hose, and containers as illustrated in Figure 14.

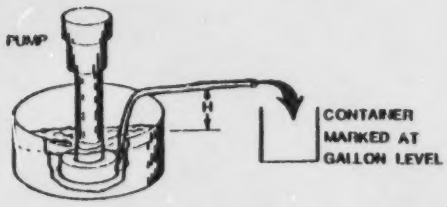



FIG. 14

2. Connect a.c. Wattmeter to pump; turn on power to pump.

3. Measure power in watts consumed by pump motor in pumping one gallon of water with hose connected for head of 0.5 ft from water level. Also measure time required to pump one gallon. Record watts and time in Data Table.

4. Repeat step 3 for the following heads: 1.0, 1.5, 2.0, and 2.5. Record.

5. Calculate and record pressure at each head. Use Equation 1.

$$p = \rho_w h \qquad (1)$$

where
$\rho_w$ = weight density of water (62.4 lb/ft$^3$).
$h$ = head (height) in feet.

6. Calculate flow rate in gal/min for each pressure head. Record.

7. Calculate and record output energy for each head. Use Equation 2.

$$E_{out} = \rho_w hV \qquad (2)$$

where
$\rho_w$ = weight density of water (8.34 lb/gal).
V = volume in gallons.

8. Calculate and record power output in ft·lb/s for each head. Use Equation 3.

$$P_{out} = \frac{E_{out}}{t} = \frac{\rho_w hV}{t} = (\rho_w h)\left(\frac{V}{t}\right) \qquad (3)$$

or

Power = pressure x volume flow rate

9. Calculate output horsepower for each head by dividing the $P_{out}$ value obtained in Equation 3 by 550 (since 1 hp = 550 ft·lb/s). Record.

10. Calculate electrical output horsepower by dividing the wattage measured at each head by 746 (since 746W = 1 hp). Record.

11. Calculate and record % efficiency of pump at each head, using values obtained and Equation 4.

$$\eta = \frac{E_{out}}{E_{in}} (100) \qquad (4)$$

12. Transfer head and overall efficiency data from Data Table to Figure 15, and plot curves.

13. Compare the curves plotted in Figure 15 to those in Figure 3 and Example A.

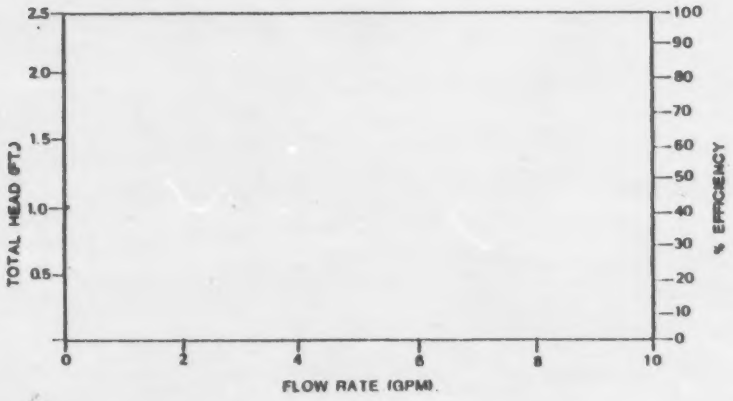



FIG. 15

| DATA TABLE | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Head (ft) | Pressure lb/in$^2$ | $P_{in}$ W | Time (s) | Flow Rate gal/min | $E_{out}$ ft·lb | $p_{out}$ ft·lb/s | $P_{out}$ hp | $P_{out}$ W | % Efficiency $\eta$ |
| 0.5 | | | | | | | | | |
| 1.0 | | | | | | | | | |
| 1.5 | | | | | | | | | |
| 2.0 | | | | | | | | | |
| 2.5 | | | | | | | | | |

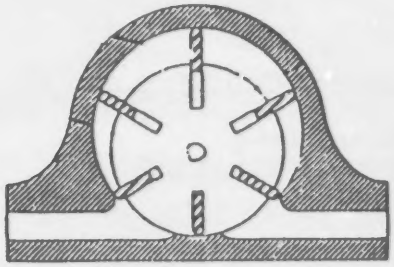
## SELF CHECK

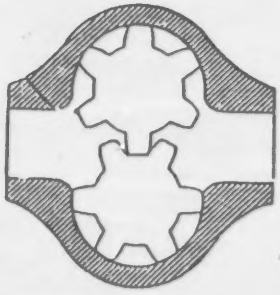
1. What are four characteristic differences between hydrodynamic pumps and positive displacement pumps?

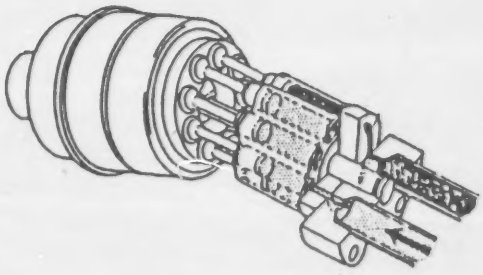
2. What is the most common application of the hydrodynamic pump?

3. What is the most common application of the positive displacement pump?

4. Identify and label the pumps in the following diagrams. Label the parts, their direction of movement, and direction of fluid flow.







5. How can unbalanced vane pumps and radial and axial piston pumps be used as variable-volume pumps?

6. How can a pump characteristic curve be of assistance in determining the size of pump required for a specific application?

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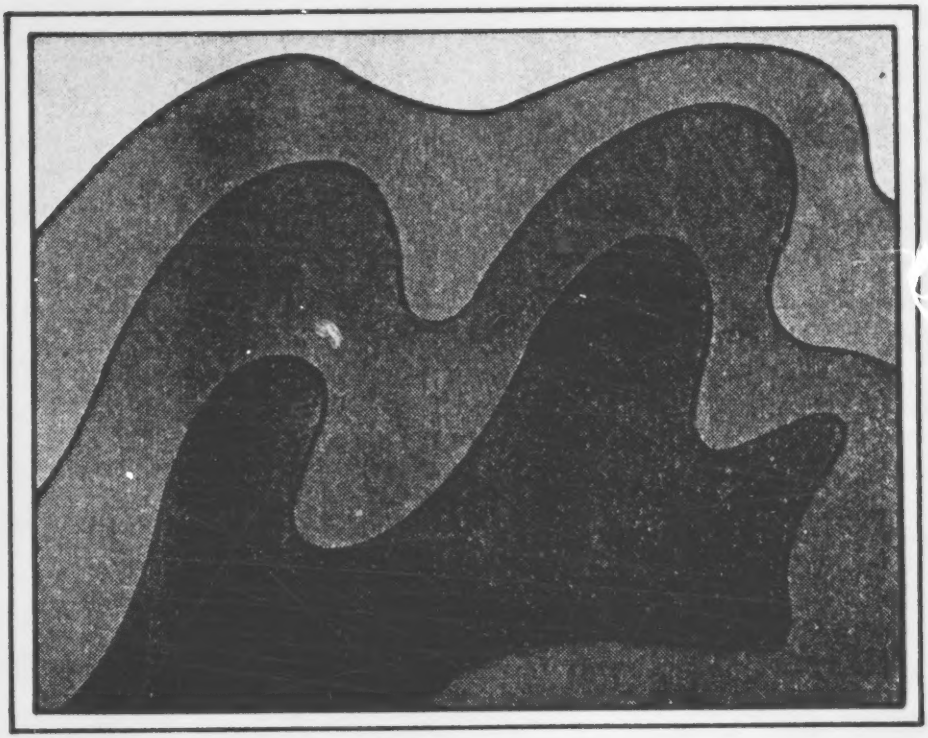
UTC

UNIFIED TECHNICAL CONCEPTS

MODULE 9 F 3

WIND POWER



# FLUID APPLICATION OF ENERGY CONVERTORS

Technical Education Research Center - Southwest

TERC - SW

## INTRODUCTION

Wind-power machines convert the kinetic energy of wind into mechanical energy, which, in turn, can be converted into electrical energy. The wind circulating above the earth's surface contains a large amount of energy that can be tapped for human needs. Wind energy has been used from ancient times for such tasks as driving ships and lifting water. Recently, there has been a revival of interest in wind power, because of increasing costs and dwindling supplies of fossil fuels. Wind generators have many designs. Multiblade types operating at relatively slow velocity deliver high torque, and are often used on farms for lifting water. Two- or three-blade generators operating at higher velocity are suitable for generating electricity. In the laboratory, the student will use a simple wind generator to produce electricity, and will measure the conversion efficiency from wind energy to electrical energy.

## PREREQUISITES

Student should have completed Concept Module 9-0, "Energy Converters."

## OBJECTIVES

Upon completion of this module, the student should be able to:

- Calculate the total power of the wind striking a windmill and the maximum theoretical power the windmill can deliver, given the wind velocity and windmill diameter.

- Given any three of the following quantities, calculate the fourth:

  Area of windmill.
  Wind velocity.
  Power delivered by windmill.
  Coefficient of performance of windmill.

- Sketch six types of windmill design.
- Define the tip speed ratio of a windmill, and state an application of a windmill with a high tip-speed ratio and an application of one with a low tip-speed ratio.
- Given the appropriate equipment, generate electricity, using a wind-powered generator; and determine the efficiency of conversion from wind energy to electrical energy.

## AVAILABILITY OF WIND POWER

The winds in the earth's atmosphere contain a large amount of energy. Some of the energy can be extracted by wind-powered machines and used to satisfy the needs of human beings.

Wind power has been used since ancient times for sailing ships, pumping water and grinding corn. Windmills were common features of the rural countryside in the United States into the 1930s, where they were used for lifting water and for generating electricity. As rural areas were gradually provided with energy from centralized supplies of electricity, the use of windmills declined. Because wind power was not always available at a particular location, people shifted to other, more constant sources of power. As a result wind power reached a low level of utilization, at least in industrialized countries.

In more recent times, there has been a revival of interest in wind power. The supply of fossil fuels is limited, and their cost is increasing. Wind is an alternative source of power which can help reduce the need for fossil fuels and, at the same time, produce power without polluting the environment. Once the wind generator has been constructed, the power that it produces is essentially free, although the cost of constructing a wind generator can be relatively high. Because wind does not blow at all times, a storage system (like batteries) is needed also, at additional cost. Thus, wind power yet does not offer a clear economic advantage compared to conventional power.

This situation may change as the cost of other fuels continues to increase. There are currently under way many experiments and developmental designs for wind generators, causing an increasing interest on the part of the public. Thus, wind power may become an increasingly important alternate source of energy.

The annual wind energy at a particular location is fairly constant. Figure 1 shows available wind power, as an annual average, over the United States. There are relatively high power areas near the northwest coast, the northeast coast, the great plains and the Great Lakes. The values indicated in Figure 1 show that there is a very substantial amount of wind power available throughout the United States.

The value of wind power available at a site depends upon characteristics of the site, such as hills and trees. Usually, a wind generator would be placed near the top of a hill in a location free of obstructions to wind. The characteristics of a particular site can be described by use of a curve that relates wind velocity to annual wind duration. Examples are shown in Figure 2 for a rather windy site and for a relatively calm site.

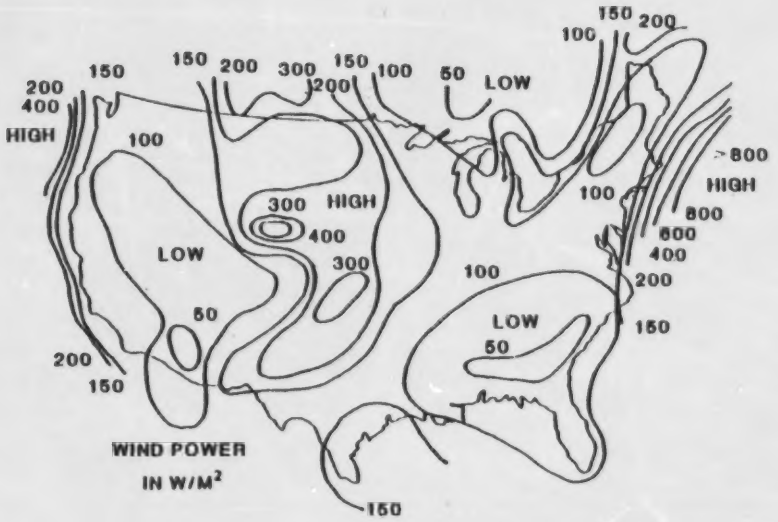



FIG. 1

A curve such as illustrated by Figure 2 should be determined when choosing a site for a windmill.

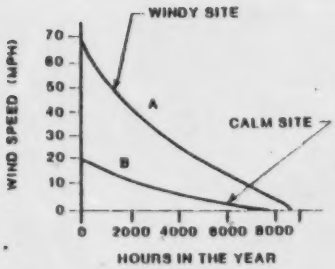



FIG. 2

## POWER DELIVERED BY A WINDMILL

Wind delivers a limited amount of energy per unit time. The kinetic energy of a mass m travelling at a velocity v is given by $\frac{1}{2}mv^2$. This formula also applies to the energy delivered by wind. If the area swept out by the blades of the windmill is given by A, the mass of air per unit time passing the windmill is given by

$$\dot{m} = \rho A v,$$

where $\rho$ is the density of air and v is the velocity of wind. When this relationship for mass is inserted into the expression for kinetic energy, the result is the power P (energy per unit time) delivered by the wind across the area swept by the blades, as indicated by Equation 1.

$$P = \frac{1}{2}\rho A v^3 \qquad (1)$$

where

P = total wind power.
ρ = density of air.
A = area of wind blades.
v = wind velocity.

Equation 1 presents the total power available for the wind driven machine. Power varies as the cube of the wind velocity, which indicates that although the power is relatively low at low wind velocities, it increases rapidly as wind velocity increases.

Power is limited also by the relatively low values of the density of air, 0.00129 gm/cm$^3$. Equation 1 must also be used with a consistent set of units, e.g., power in watts, density in kilogram/meter$^3$, area in meter$^2$ and wind velocity in meter/s. Rewriting Equation 1 to include appropriate units yields a form that may be easier to use, as shown in Equation 2.

$$P = 1.37 \times 10^{-5} Av^3 \qquad (2)$$

where

P = total wind power in kilowatts.
A = area of wind blades in square meters.
v = wind velocity in km/hour.

Not all this power may be extracted from the wind. The energy developed by a wind machine comes from slowing down the wind. If the wind machine extracted all the energy, wind velocity would drop to zero behind the blades. The maximum fraction of energy that may be extracted from the wind is 0.593. The maximum value of the power that may be extracted from the wind is presented by Equation 3.

$$P_{max} = 0.593 \times 1.37 \times 10^{-5} Av^3$$
$$P_{max} = 8.12 \times 10^{-6} Av^3 \qquad (3)$$

where

$P_{max}$ = maximum power extractable from wind.

The actual power output from a real wind machine is less than this theoretical maximum. Ap is the coefficient of performance, or the actual power generated, divided by the power delivered by the wind. If $P_{actual}$ is the actual power developed by the wind machine, the coefficient of performance can be derived with Equation 4.

$$Ap = \frac{P_{actual}}{1.37 \times 10^{-5} Av^3} \qquad (4)$$

where

$\Delta p$ = coefficient of performance.

$P_{actual}$ = actual power developed by a wind machine.

The coefficient of performance is, thus, the efficiency for transforming wind energy. The maximum possible value for the coefficient of performance is 0.593, as discussed above. The use of Equations 2, 3 and 4 is shown in Example A to solve a problem.

**EXAMPLE A: POWER DELIVERED BY A WINDMILL**

Given: A windmill has a blade radius of 1.5 meter. At a wind velocity of 20 km/hr, it generates 200 watts.

Find:
(a) Power delivered by the wind.
(b) Theoretical maximum power that the windmill could generate.
(c) Coefficient of performance.

Solution: The area A swept by the blades is $\pi r^2$, where r is the radius.

$$A = \pi(1.5)^2 = 7.07 \text{ square meters.}$$

From Equation 2, the power delivered by the wind is:

$$P = 1.37 \times 10^{-5} \times 7.07 \times (20)^3 = 0.775 \text{ kw}$$

The maximum theoretical power from the windmill is:

$$P_{max} = 0.593 \times 0.775 = 0.460 \text{ kw}$$

The realized power is 0.2 kw; therefore, the coefficient of performance is:

$$\Delta p = 0.2/0.775 = 0.258$$

Equations 1 and 2 indicate that the power generated by a wind machine increases rapidly with increasing wind velocity. This increase does not continue indefinitely, because of practical considerations. There is a maximum speed at which the wind gen-

erator can be allowed to turn. Otherwise, the generator could be damaged by excessive speed or by vibration. Thus, windmills are equipped with speed governors that limit the maximum velocity at which the blades can turn. Governors protect windmills from destruction by very high winds.

A particular wind generator may be described by a characteristic curve, as illustrated in Figure 3. At low wind velocity, the power generated is very small; consequently, there is a cut-in point, below which no power is generated. As wind velocity increases, power increases as the cube of the wind velocity. At the maximum rated wind speed, the governor is actuated to limit the speed of the windmill in order that generated power is constant at higher wind speeds.

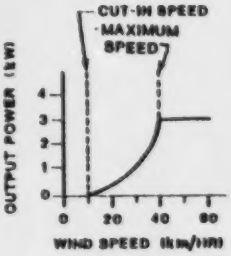


FIG. 3

Another important characteristic of windmills is the tip speed ratio, which is defined as velocity of the blade tip divided by velocity of the wind. Velocity of the blade tip is determined by Equation 5.

$$v_{tip} = 2\pi rf \qquad (5)$$

where

$v_{tip}$ = velocity of blade tip.
$\pi$ = pi, 3.14159.
$r$ = radius of blade.
$f$ = frequency of blade rotation.

Tip-speed ratio is given in Equation 6.

$$\frac{v_{tip}}{v_{wind}} = 2\pi rf/v \qquad (6)$$

where

$v_{wind}$ = wind velocity.

Note: the numerator and denominator of the ratio must be in the same units. Thus, if $r$ is expressed in meters and $f$ in revolutions/minute, $v$ must be expressed in meters/minute.

The tip-speed ratio depends on the design of the windmill. Values for the tip speed ratio of practical windmills may range from approximately 1 up to about 8. Different types of wind generators operate best at their own optimum tip speed ratio. Windmills designed for lifting water operate best with a tip speed

ratio of about 1; whereas, windmills designed for generating electricity operate at high blade velocity, with tip-speed ratios up to 7 or 8.

## WINDMILL DESIGNS

There are numberous windmill designs, some very familiar. Most windmills have blades mounted on a horizontal axis, with the propellor rotating in a plane perpendicular to the wind. For greater efficiency, the propellor and shaft should be free to rotate, in order that the propellor can face the wind. Several types of horizontal axis designs are as follows:

MULTIBLADE TYPE

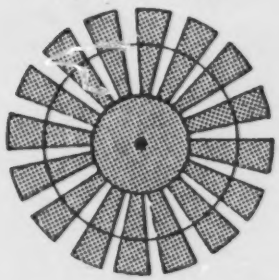


FIG. 4

- The multiblade mill. This type, with the propellor design shown in Figure 4, is a familiar sight on the American countryside, where it long has been used for pumping water on farms. It is a relatively low-speed, high torque design, best suited for lifting water, but not well adapted for generating electricity. This design is sometimes called a fan type.

- The four-arm Dutch type. This type, illustrated in Figure 5, is also very familiar. It can be very large, with blades up to 100 feet in diameter. The Dutch type is slow in speed, and has been used for grinding corn and for similar tasks.

DUTCH 4 - BLADE MILL

FIG. 5

- Sail windmills. This type is less familiar in the United States. It is widely used in Mediterranean countries. The basic design is displayed in Figure 6. The sail mill is made from sail cloth fastened to wooden spars. The sail mill is also a low-speed design, best suited for tasks such as pumping water. It uses inexpensive materials.

- High-speed 2 or 3 blade types. This represents a more advanced type of propellor design, with blades constructed for minimum drag. Blades are long and slender, and rotate at high speed, with tip speed ratios greater than 5. Such a design provides low torque, which makes it less adapted than other designs for lifting water. Since it does provide efficient generation of electricity, most wind generators use this design. The blades fill only a small fraction of the area they sweep, as indicated by Figure 7.

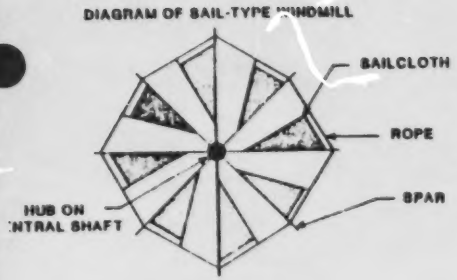



FIG. 6

FIG. 7

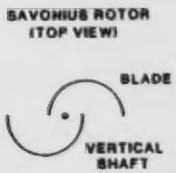



FIG. 8

There are also windmills which have a vertical axis. The blades then move in the direction of the wind. A vertical-axis windmill does not require orientation into the wind. There are two vertical axis designs:

- The savonius rotor. This design has two curved surfaces that appear from the top as shown in Figure 8. This low-speed design is suitable for pumping water.

- The Darrieus rotor is a high-speed design that employs two or more long, thin blades. A drawing of a typical design with curved blades attached to the vertical shaft is shown in Figure 9. The Darrieus rotor is suitable for genration of electrical power.

In addition to these designs, there are numerous experimental types that offer some possibilities for high efficiency with low cost and simple construction.

FIG. 9

## CHARACTERISTICS OF VARIOUS DESIGNS

Figure 10 shows the coefficient of performance (Equation 4) versus tip speed ratio, for a number of designs. Each design has a maximum value of coefficient of performance at a particular speed. For example, the multiblade type has a maximum coefficient of performance of 0.3 at a tip speed ratio near 1.0. The lower-speed designs are better suited for tasks like lifting water. The higher-speed ones are suitable for generating electricity. The highest values of coefficient of performance are offered by the high-speed, two-blade design, which can offer values between 0.4 and 0.5. (The maximum value possible is 0.593.)

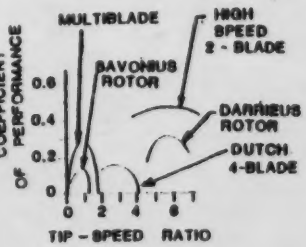
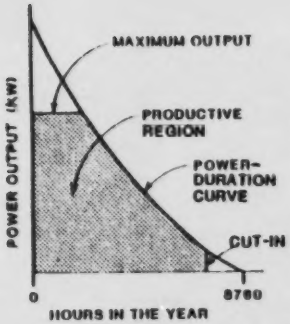



FIG. 10




PRODUCTIVITY GRAPH FOR A WIND GENERATOR

FIG. 11

The characteristic curve for a particular wind generator (Figure 3) may be weighted by the velocity duration characteristic of the site at which it is located (Figure 2). This process yields a power-duration curve, as illustrated in Figure 11. The area under the curve is a measure of the productivity of a particular generator at its particular location. The total area under the curve would be the output if there were no practical limitations due to wind velocity. The straight vertical line indicates where there is no output below the cut-in point when the wind is nearly still. The straight horizontal line indicates where the output is limited by the speed governors in high winds. The shaded area represents the actual productivity after these limitations are accounted for.

## ECONOMIC CONSIDERATIONS

An economic analysis of the feasibility of a windmill system must include some estimate of the lifetime of the windmill. A well-designed and well-constructed windmill, with proper care, could last at least 20 years. Experience has shown that many windmills are still in operation after 30 or 40 years.

Example B is an economic analysis for a particular case. This example shows some of the factors that must be included in such an analysis. It is intended only as a representative case, rather than as a full analysis applicable to all cases. It also depends upon several assumptions about lifetime and about future costs of electricity.

**EXAMPLE B: COST OF WIND POWER**

**Given:** A wind generator capable of supplying 600 kwh per month can be purchased and installed at a cost of $5,000. If the money were left in a bank, it would earn 5% interest, compounded annually. Electricity now costs 4¢/kwh, and the cost will increase 10% per year. Assume that the windmill will last 20 years.

**Find:** The total savings over the lifetime of the windmill.

**Solution:** The initial cost is $5,000. In the first year, the cost of lost interest is 0.05 x 5000 = $250. In the second year, the cost is 0.05 x 5250 = $263. The interest cost for each year and the cumulative costs are summarized in Table 1.

The saving on electricity in the first year is 600 kwh/month x 12 months x 0.04/kwh = $288. In the second year, the saving is 1.1 x 288 = $317. The saving in each year and the cumulative savings are also summarized in Table 1.

Over the 20-year lifetime, there would be a total savings of $16,506 - $13,268 = $3,238.

TABLE 1: SUMMARY OF COSTS AND SAVINGS IN EXAMPLE B

| Year | Interest Lost | Cumulative Cost | Savings | Cumulative Savings |
|---|---|---|---|---|
| 1 | $250 | $ 5,250 | $ 288 | $ 288 |
| 2 | 263 | 5,513 | 317 | 605 |
| 3 | 276 | 5,789 | 349 | 954 |
| 4 | 289 | 6,078 | 384 | 1,338 |
| 5 | 304 | 6,382 | 422 | 1,760 |
| 6 | 319 | 6,701 | 464 | 2,221 |
| 7 | 335 | 7,036 | 511 | 2,735 |
| 8 | 352 | 7,388 | 562 | 3,297 |
| 9 | 363 | 7,757 | 618 | 3,915 |
| 10 | 388 | 8,145 | 680 | 4,595 |
| 11 | 407 | 8,552 | 747 | 5,342 |
| 12 | 428 | 8,980 | 822 | 6,164 |
| 13 | 449 | 9,429 | 904 | 7,068 |
| 14 | 471 | 9,900 | 995 | 8,063 |
| 15 | 495 | 10,395 | 1,094 | 9,157 |
| 16 | 520 | 10,915 | 1,204 | 10,361 |
| 17 | 546 | 11,461 | 1,324 | 11,685 |
| 18 | 573 | 12,034 | 1,457 | 13,142 |
| 19 | 602 | 12,636 | 1,602 | 14,744 |
| 20 | 632 | 13,268 | 1,762 | 16,506 |

## SUMMARY

Wind power is produced by machines that convert wind energy into mechanical energy used for a variety of purposes, the most promising and practical of which is generation of electrical power. Wind power is especially promising in localities having high average wind energy. Characteristics and efficiency of various wind-powered machines can be calculated.

## WIND - POWER GENERATION OF ELECTRICITY

### MATERIALS

Anemometer (Edmund Scientific has several models in the price range $29.50 - $59.50; Sencenbaugh Wind Electric, Mountain View, California has a model at $115).
Ammeter.
Voltmeter.
Storage battery (such as automobile battery).
Meter Stick.
Electrical wiring and connectors, as needed.
Small wind-powered electrical generator.

Option 1. Purchase Commercial Unit. Models are available from Sencenbaugh Wind Electric Co. (Model 24-14, rated at 24 watts at 21 mph wind speed) for $385, and from Edmund Scientific Co. (200 watts at 25 mph wind speed) for $550.

Option 2. Construct a Small Generator. This option may involve too much labor for each student to construct his own generator in the course of this module. Possibly an entire class, working together, could construct it. Or possibly a model could be constructed as part of a larger application project, and used by other students, as needed. Materials needed for wind generator:

- Sailcloth and rope.
- Wooden spars.
- Staples and staple gun.
- Metal shaft and hub.
- Pillow blocks (2).
- One-foot diameter wheel to fit shaft.
- Automotive generator.
- Automotive generator belt.
- Lumber, nails, screws and tools, as needed for constructing a mounting platform.

A sail mill is suggested, as being inexpensive and easy to construct. It may be made simply from sail cloth attached to wooden spars. However, if another propellor is available, it could be used instead; for example, a multiblade fan from an old farm windmill.

The basic structure of the sail mill is shown in Figure 6. Attach wooden spars to hub by drilling holes and using screws. Lash ends of the spars together with rope. Cut triangular sails from sail cloth, and attach with rope and staples. When propellor is completed, attach hub to metal shaft.

Construct a wooden mounting platform to serve as a rigid mount for components. When the unit has been completed, the entire structure can be moved manually to face into the wind.

Fasten pillow blocks to the wooden frame, and mount shaft in the pillow blocks. Attach wheel to shaft on opposite end from the propellor, as shown in Figure 12. Mount generator on the frame. The generator must be located in such a manner that belt will be tight between wheel and generator.

The description above may be varied according to availability of different materials.

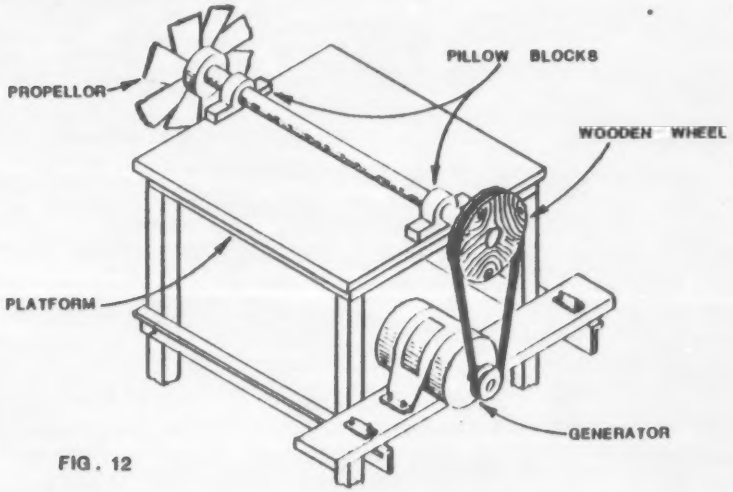



FIG. 12

## PROCEDURES

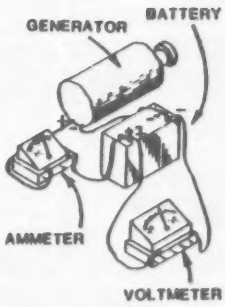



FIG. 13

The student will use a small wind generator to generate electricity, and will measure the efficiency of the conversion from wind energy to electrical energy.

1. On a day with a resonable wind, move wind generator outdoors. If propellor does not rotate to face wind, rotate it manually into wind.

2. Connect output terminals of generator to battery, as shown in Figure 13. For maximum output, battery should be nearly discharged. Allow propellor to turn in wind.

3. Use ammeter in series with generator to measure current I; record I in Data Table.

4. Use the voltmeter in parallel with generator and battery to measure voltage E.

5. Use anemometer to measure wind velocity v; record. (Follow instructions provided by the manufacturer of the anemometer.)

6. Use meter stick to measure radius r of blades; record. (Area A swept by the blades is $A = \pi r^2$.)

7. Calculate and record coefficient of performance for wind generator. Coefficient of performance is electrical power divided by wind power. Use Equation 1 or 2 for wind power. (Electrical power is equal to IE.)

8. How does the coefficient of performance of the laboratory wind-powered generator compare with that of Example A? Explain any differences in the two.

| DATA TABLE | | | | | | |
|---|---|---|---|---|---|---|
| Current to Generator I | Voltage to Generator E | Wind Velocity v | Radius of Blades r | Electrical Power IE | Wind Power | Coefficient of Performance Ap |
| | | | | | | |

## SELF CHECK

1. The velocity of the wind striking a windmill 8 m in diameter is 32 km/h. Find the following values:

   a. Total wind power striking the windmill.
   b. Maximum theoretical power that the windmill could deliver.

2. The above windmill delivers a power of 11 kw. What is its coefficient of performance?

3. A windmill with an area of $25m^2$ has a coefficient of performance of 0.35. What power does it deliver with a wind velocity of 25 km/h?

4. Sketch 4 types of windmill design.

5. Define tip-speed ratio of a windmill.

6. Given an application of a windmill with these tip ratios:

   a. High tip-speed ratio.
   b. Low tip-speed ratio.

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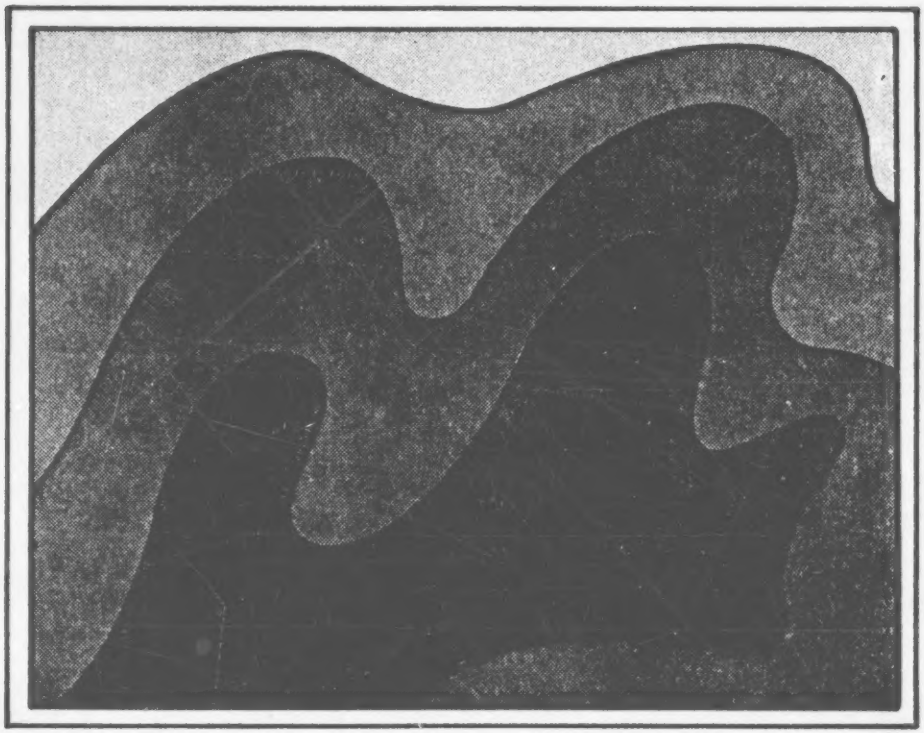
UNIFIED TECHNICAL CONCEPTS

MODULE 9 F 4

FANS AND BLOWERS



FLUID APPLICATION OF ENERGY..CONVERTORS

Technical Education Research Center - Southwest

TERC - SW

## INTRODUCTION

Fans and blowers are energy converters that use both electrical and mechanical energy to produce fluid energy. In a fan or blower, the electrical energy of the motor is converted into the rotational mechanical energy of the fan blades. The mechanical energy of the fan blades then moves the air through the discharge duct, thereby creating fluid energy. The ability to move air and other fluids through ducting systems is basic to air conditioning and heating technologies and plays a major role in many other areas of technological society. This module presents the theory of operation and basic design of fans and blowers. In the laboratory, the student will determine the air horsepower and the efficiency of a fan motor.

## PREREQUISITES

Student should have completed Concept Module 9-0, "Energy Converters."

## OBJECTIVES

Upon completion of this module, the student should be able to:

- Define the following terms:

  Air horsepower.
  Power input.
  Static efficiency.
  Static pressure.
  Total pressure
  Velocity pressure
  Mechanical efficiency.

- Given the static pressure, velocity pressure, volume flow rate, and shaft horsepower of a fan, determine its static and mechanical efficiency.

- Given a schematic representation of an axial flow fan and a radial flow fan, correctly identify each; and indicate the direction of air flow on both diagrams.

- Given the schematic representation of six different blade types in a centrifugal (radial) fan, correctly identify and label each of the blade types.

- Given a schematic representation showing four different inlet designs for a propellor, draw the air flow for each design. Indicate which of these four systems is most efficient.

- Given the appropriate equipment, measure the velocity of air through an air discharge duct and the static and velocity pressures; from these measurements determine the air horsepower and the efficiency of the fan motor.

## DISCUSSION

Fans, blowers, and compressors move air, but at greatly different pressures. Fan pressures range from a few inches of water up to about 1-psi. Blowers work to about 50-psi; compressors operate from about 35-psi and up. Since fans, blowers, and compressors all basically do the same thing, this module discusses only fans. When appropriate, important differences between the three will be pointed out.

A fan can be defined as a volumetric machine that operates very much like a pump. In simple terms, a fan moves quantities of gas or air from one place to another. In doing this, it overcomes resistance to flow by supplying the fluid with the energy necessary for continued motion. Physically, the essential elements of a fan are a bladed rotor (such as an impeller or propeller) and a housing in which to collect the incoming air or gas and to direct its flow. Figure 1 displays the essential elements of a fan.

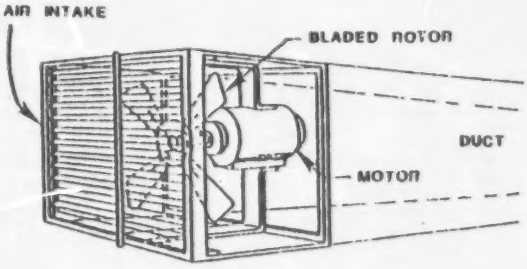



FIG. 1

### WORK OF A FAN

Since any device that makes something else move is doing work, a fan requires energy for operation. The amount of energy required depends upon the volume of gas moved, the resistance against which the fan works, and the machine efficiency.

These energy relationships are clarified by the pressure-volume diagram shown in Figure 2 for a typical fan and compressor. From point 1 to point 2 in the fan cycle, there is very little pressure change in the suction phase. During this phase, air is sucked into the intake of the fan at constant pressure until the volume at point 2 is reached. At this point the fan blade compresses the air slightly, increasing the pressure. This step is shown as the compression phase in Figure 2 (point 2 to point 3). From point 3 to point 4, the fan is discharging the gas at constant pressure. At point 4, the gas has been completely discharged from the fan

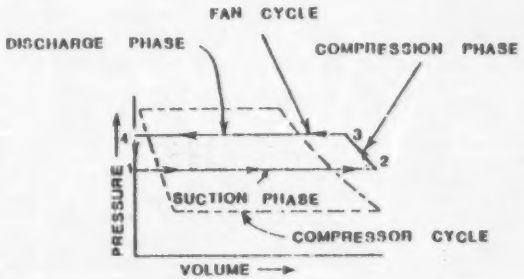



FIG. 2

outlet. The fan then shows a drop in pressure back to point 1, where the cycle is repeated. The work done by the fan is equal to the area enclosed by the fan cycle. Figure 2 also demonstrates that the pressure changes involved are relatively minor.

Also shown in Figure 2 is the pressure-volume diagram for a compressor. Notice that the compressor cycle operates over a much larger pressure range; otherwise, the diagram is similar in every respect to that for the fan. Unlike blowers or compressors, which work against larger pressures and significant pressure increases, the bulk of fan work goes into moving gas at a relatively low pressure. Notice also from Figure 2 that the volume remains virtually constant during the compression phase because the change in specific weight of the gas between fan inlet and discharge is negligible; in fact, for a 1-psi pressure increase, the specific weight of air changes by less than 7%. Thus, when fan power is analyzed, the volume change during the compression phase can be thought of as zero. Work accomplished by the fan cycle is expressed accurately by Equation 1.

$$W = V\Delta p \tag{1}$$

where

$W$ = work done in fan cycle.
$\Delta p$ = rise in pressure across the fan.
$V$ = volume of air or gas moved.

Pressure difference (either static or total) usually is measured in inches of water. Static pressure is the force per unit area exerted on walls and ducts — like the steam pressure on the inside of a boiler drum. Static pressure is that pressure that overcomes the resistance of the ducts.

Total pressure represents the combined effect of static pressure and velocity pressure. Velocity pressure is that pressure over and above static pressure caused by the movement of the air or gas. Figure 3 illustrates how manometers inserted in a fan discharge duct measure static pressure, velocity pressure, and total pressure. The total pressure in a duct is given by Equation 2.

$$p_t = p_s + p_v \tag{2}$$

where

$p_t$ = total pressure in duct.
$p_s$ = static pressure.
$p_v$ = velocity pressure.

## AIR HORSEPOWER

From Equation 1, an equation can be developed to express "air horsepower." Air horsepower is defined as "the horsepower required at 100% fan efficiency to move a given quantity of air against a given pressure." The resulting expression for air horsepower Ahp is given by Equation 3.

$$Ahp = \frac{Q_v \Delta p}{6356} \qquad (3)$$

where

$Ahp$ = air horsepower.
$Q_v$ = volumetric flow (flow rate) through the fan in cubic feet per minute.
$\Delta p$ = pressure difference across the fan in inches of water.

The air horsepower also may be designated as "static" or "total." Since the resistance to be overcome in fan applications is primarily static pressure, the fan pressure developed usually is referred to as "static pressure." On this basis, the calculated fan power is known as "static air horsepower," as given by Equation 4.

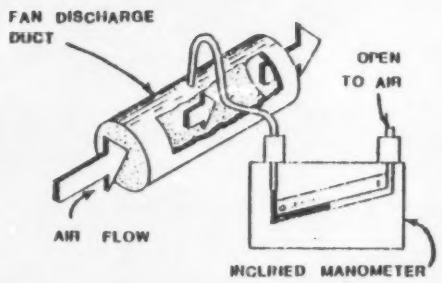
$$Ahp_s = \frac{Q_v \Delta p_s}{6356} \qquad (4)$$

where

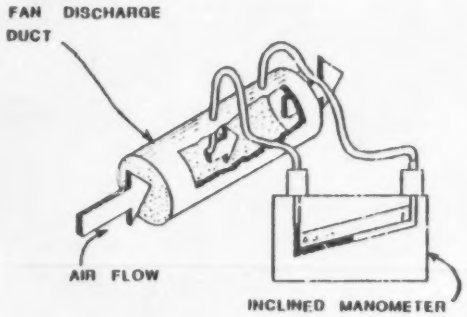
$Ahp_s$ = static air horsepower.
$\Delta p_s$ = static head pressure in inches of water.

When the power calculations are based upon total pressure, fan power is referred to as the "total air horsepower" and is equivalent to the output

STATIC PRESSURE




VELOCITY PRESSURE




TOTAL PRESSURE

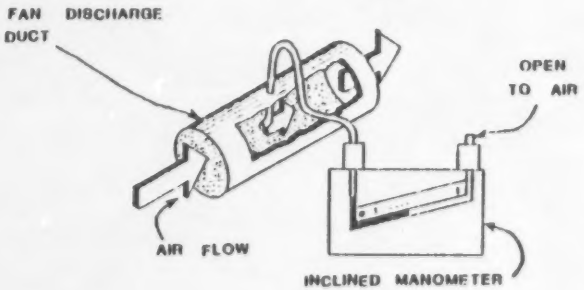



FIG. 3

power. Total air horsepower is derived from Equation 5.

$$Ahp_t = \frac{Q_v \Delta p_t}{6356} \tag{5}$$

where

$Ahp_t$ = total air horsepower.
$\Delta p_t$ = total head pressure in inches of water.

## EFFICIENCY

In similar fashion, static efficiency is associated with $Ahp_s$; and mechanical efficiency, or total efficiency, is associated with power output. Each is compared with shaft horsepower, or the power input to the fan, to arrive at an actual efficiency figure. Equation 6 is for static efficiency.

$$\eta_s = \frac{Ahp_s}{P_{in}} \tag{6}$$

where

$\eta_s$ = static efficiency.
$P_{in}$ = power input to fan.

Mechanical, or total, efficiency is given by Equation 7.

$$\eta_t = \frac{Ahp_t}{P_{in}} \tag{7}$$

where

$\eta_t$ = mechanical (total) efficiency.

Many small variables influence the power output efficiency of any fan; such things as pressure and temperature are the most important. For the purposes of this module, no corrections are made for temperature and pressure variations of the air or gas.

Equations 6 and 7 are utilized to find the solution to a problem in Example A.

| EXAMPLE A: STATIC AND MECHANICAL EFFICIENCY | |
|---|---|
| Given: | A fan used for air conditioning and heating develops 4.5-inch static pressure and 0.7-inch velocity pressure when flow is 8,000 cfm of 100°F air; shaft horsepower is 7.2 hp. |
| Find: | (a) Static efficiency. |

(b) Mechanical efficiency.

Solution: (a) $Ahp_s = \frac{Q_v \Delta p_s}{6356}$ (Equation 4)

$= \frac{(8000)(4.5)}{6356}$

$Ahp_s = 5.7$ hp

$\eta_s = \frac{Ahp_s}{P_{in}}$ (Equation 6)

$= \frac{5.7 \text{ hp}}{7.2 \text{ hp}}$

$\eta_s = 79\%$

(b) $\Delta p_t = \Delta p_s + \Delta p_v$ (from Equation 2)

$= 4.5 \text{ in} + 0.7 \text{ in}$

$\Delta p_t = 5.2$ in

$\eta_t = \frac{Ahp_t}{P_{in}}$ (Equation 7)

$= \frac{6.54}{7.2}$

$\eta_t = 91\%$

## THE TWO FAN TYPES

There are two basic classes of fans: (1) the axial-flow design, which moves gas or air parallel to the axis of rotation, and (2) the centrifugal-flow (or radial-flow) type, which moves air or gas perpendicular to the axis of rotation. Axial-flow fans are better suited to low resistance applications. Centrifugal-flow fans usually take care of the higher pressure jobs.

The axial-flow fan uses the screwlike action of a multi-bladed rotating shaft or propeller to move air or gas in a straight-through path. The leading edge of each rotating propeller blade bites into the air or gas, which is then propelled through the fan and discharged in a helical pattern, as shown in Figure 4, by the blades' trailing edge.

The efficiency of a propeller fan depends largely upon its inlet design because air recirculation around blade tips greatly reduces the efficiency of a propeller-type fan. Installation of a curved orifice-like ring at the blade tips reduces the amount of recirculation and improves efficiency. An angle-shaped ring almost eliminates recirculation. Optimum efficiency is achieved with a combination curved, angle-shaped

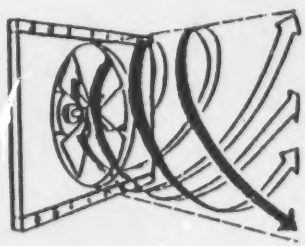


FIG. 4

ring, which also smoothens flow. The flow patterns for the air recirculating around the blade tips of these various inlet designs is illustrated in Figure 5.

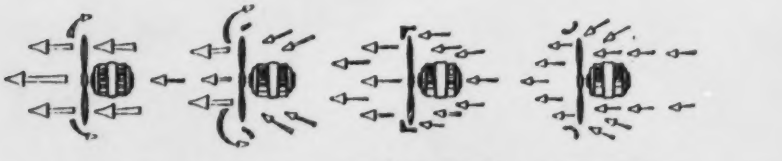



FIG. 5

Two common varieties of axial flow fans are exhibited in Figure 6.

The tube-axial design is nothing more than a propeller fan enclosed in a cylinder that collects and directs air flow. In a vane-axial fan (an extension of the tube-axial design), air guide vanes on the air discharge side of the propeller straighten out the air flow pattern and increase static pressure.

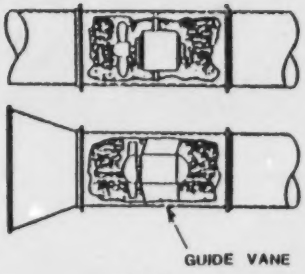



FIG. 6

Axial-flow fans can have widely-differing characteristics, depending upon the design, blade type, and ducting. Generally, they are applied where the required outlet velocities are higher than can be produced by centrifugal-fans and when pressure demands are not above actual flow limits.

Centrifugal, or radial, fans are advantageous when the air must be moved in a system in which the frictional resistance is relatively high (Figure 7). The air drawn into the center of the revolving wheel turns 90° and enters the space between the blades in the wheel. The bladed wheel whirls air centrifugally between each pair of blades and tosses it out peripherally at high velocity and increased static pressure. As this happens, more air is sucked in at the eye of the wheel. As the air leaves the revolving blade tips, part of its velocity is converted into additional static pressure by divergence of the scroll-shaped housing.

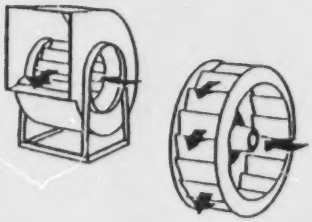


FIG. 7

Blade shapes employed are of three basic

types: forward curved, straight, and backward curved. Other configurations, including an air foil design, are merely variations of these designs. Some commonly-used shapes are given in Figure 8.

In general, blade type limits top fan speed. Backward-curved blade machines can operate at a higher speed than forward-curved designs. The type of blade employed also depends upon space limitations, allowable noise levels, efficiency demanded by specified load conditions, and desired fan performance characteristics. While mechanical efficiencies are much the same for each different blade type, differences in horsepower and pressure-volume relationships can be significant.

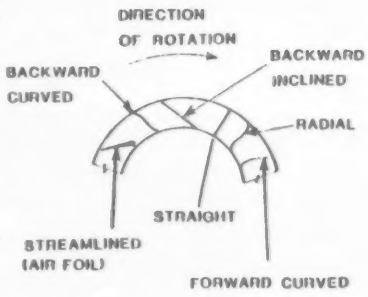



FIG. 8

## SUMMARY

A fan requires energy to move gas or air through a duct system. The amount of energy required depends upon the volume of gas moved, the resistance of the duct system, and the machine efficiency. The efficiency of a fan can be calculated once the volumetric flow through the fan and the pressure difference across the fan are known. There are two basic classes of fans: the axial-flow design and the centrifugal-flow type. Each of these classes has efficiencies that depend, amoung other things, upon inlet design and blade types. In general, axial-flow fans are better suited to low-resistance applications; and centrifugal flow fans are used in higher-pressure applications.

## AIR HORSEPOWER AND EFFICIENCY OF A FAN MOTOR

### MATERIALS

Fan – FE Cat. No. F13S107, 110-120 V, 60 cycle, 0.6 A (or any equivalent axial fan).
Manometer – Dwyer incline portable Module 102 or Ellison inclined portable with hemispherical pitot.

### PROCEDURE

1. Arrange fan and discharge duct as shown in Figure 9. If fan does not have a discharge duct, fabricate one out of galvanized steel or other suitable material.

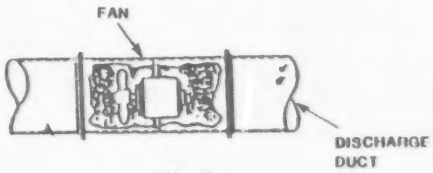


FIG. 9

2. Record fan horsepower in Data Table as power input.

3. With fan on, measure the total pressure, static pressure, and velocity pressure as shown in Figure 3. Record results in Data Table.

4. Calculate air velocity from the relationship –

$$v = \frac{1096.2\ p_v}{\rho}$$

where
$v$ = air velocity.
$p_v$ = velocity pressure in inches of water.
$\rho$ = air density (0.75 lb/cu ft).
Record in Data Table.

5. From the following relationship, calculate volumetric flow rate; record in Data Table.

$$Q_V = Av$$

where
$Q_V$ = volumetric flow rate in $ft^3/min$.
$A$ = duct area in $ft^2$.
$v$ = air velocity in ft/min.

6. Calculate and record the static air horsepower $Ahp_t$ and static efficiency $\eta_s$. Record results in Data Table.

$$Ahp = \frac{Q_v \Delta p_s}{6356}$$

$$\eta_s = \frac{Ahp_s}{P_{in}}$$

7. Calculate and record the total air horsepower $Ahp_t$ and the mechanical efficiency $\eta_t$.

$$Ahp_t = \frac{Q_v \Delta p_t}{6356}$$

$$\eta_t = \frac{Ahp_t}{P_{in}}$$

| DATA TABLE | |
|---|---|
| Power Input = $P_{in}$ = _____ | hp |
| Total Pressure = $p_s + p_v$ = _____ | in of $H_2O$ |
| Static Pressure = $p_s$ = _____ | in of $H_2O$ |
| Velocity Pressure = $p_v$ = _____ | in of $H_2O$ |
| Air velocity = v = _____ | ft/min |
| Flow rate = $Q_v$ = _____ | $ft^3$/min |
| $Ahp_s$ = _____ | hp |
| Static Efficiency ($\eta_s$) = _____ | % |
| $Ahp_t$ = _____ | hp |
| Mechanical Efficiency ($\eta_t$) = _____ | % |

## SELF CHECK

1. Write a formula for the following terms:

Total pressure $p_t$ =

Static air horsepower $Ahp_s$ =

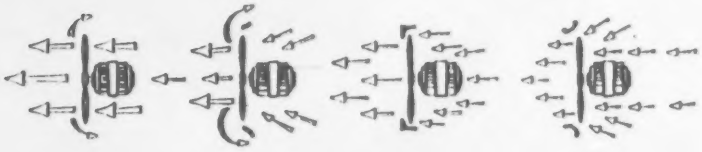
Total air horsepower $Ahp_t$ =

Static efficiency $\eta_s$ =

Mechanical efficiency $\eta_t$ =

2. Prepare a drawing that illustrates the air flow through a radial-flow fan and through an axial-flow fan.

3. Label the blade types illustrated below, and identify the most efficient fan inlet shown.



4. A fan produces a static pressure of 2.5 inches of water and a velocity pressure of 0.5 inches of water. The flow rate is 3600 cfm. The input horsepower is 2 hp. Determine the static efficiency and the mechanical efficiency of the fan.

5. A fan with an input power of 1 hp produces a flow rate of 2000 cfm with a static pressure of 2.6 inches of water. The mechanical efficiency of the fan exceeds the static efficiency by 10%. Determine the velocity pressure produced.

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See especially Parts 1, 2, and 3, AMCA Publications 201, 202, and 203.

Kahoe, H. Taylor, ed. "The Air Conditioning and Refrigeration Business." Testing/Balancing Lab, April 1968, pp. 56-58.

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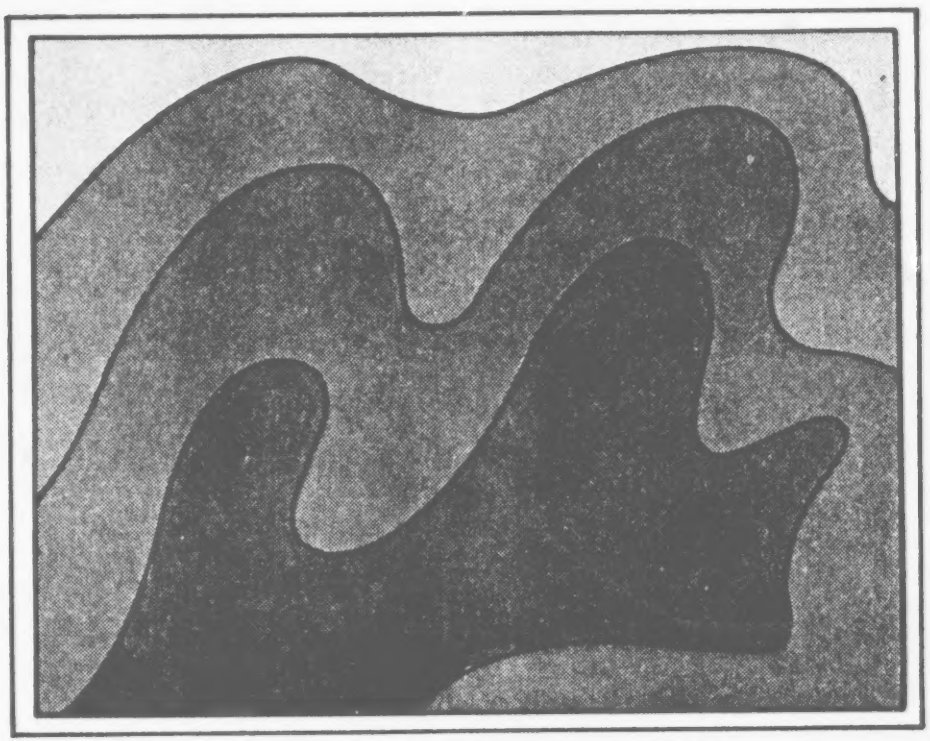
UNIFIED TECHNICAL CONCEPTS

MODULE 9 F 5

VACUUM PUMPS



FLUID APPLICATION OF ENERGY CONVERTORS

Technical Education Research Center - Southwest

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# INTRODUCTION

## VACUUM PUMPS

A number of different pumps are used to produce a vacuum in enclosed chambers. These pumps include rotary mechanical pumps, diffusion pumps, sputter-ion pumps, and cryogenic pumps. The pressure ranges that can be covered vary from one pump type to another. In common practice, a mechanical pump is used to pump down from atmospheric pressure to medium vacuum; and then a second pump is switched on to reach high or ultrahigh vacuum.

In the laboratory, the student will use at least two different pump types to evacuate a vacuum system and will measure the pressure in the system during pump-down.

# PREREQUISITES

Student should have completed Concept Module 9-0, "Energy Converters." We recommend that the student be acquainted with vacuum gages as treated in Application Module 10F5, "Vacuum Gages."

# OBJECTIVES

Upon completion of this module, the student should be able to:

- Define the following terms:

  Pumping speed.
  Conductance for flow of gas through a pipe.
  Impedance for flow of gas through a pipe.
  Pump-down time.

- Given the necessary information, calculate the time required for a pump to pump down a specific volume.

- Given the necessary information, calculate the impedance for flow of gas through a specific section of pipe.

- Describe the operation of the following types of pump:

  Rotary mechanical pumps.
  Diffusion pumps.
  Sputter-ion pumps.
  Cryogenic pumps.

- State the approximate pressure range covered by each of the above pump types.

- Given the appropriate equipment, evacuate a vacuum chamber, and measure the pressure during pump-down, using —

  A mechanical pump alone.
  A mechanical pump plus either an oil-diffusion pump or a sputter-ion pump.

## DISCUSSION

This module emphasizes the operation of the various types of pumps commonly used to evacuate vacuum systems. The concepts of degree of vacuum, gas pressure, and mean free path presented in Application Module 10F5 will be taken for granted.

A pump for reducing pressure in a chamber may be characterized by its pumping speed. The pumping speed measures the rate at which gas is removed by the pump. It has units of volume per unit time; for example, liter/second. The definition of pump speed is the volume of gas per unit of time removed from the system at the pressure existing at the inlet to the pump. Note: Pump speed is specified for the pressure at the inlet. As the pressure is decreased for a constant pump speed, therefore, the volume of gas removed is the same; but since the pressure of the gas in continually being reduced, the quantity of gas (e.g., the number of gas molecules) removed per unit time is continually decreasing.

Pump speed is a function of gas pressure. Figure 1 shows a typical curve that defines pump speed versus pressure. At some high value of pressure, the pump will not work well, and the pump speed will be low. Also, when the pressure becomes very low, the pump again is incapable of removing the gas. Over a range of pressures between these limits, the pumping speed will be reasonably constant. (The pressure range over which various types of pumps are useful will be described later.) The pressure range over which pump speed is constant may cover several orders of magnitude.

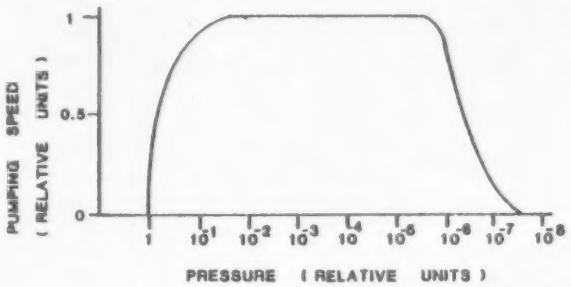



FIG. 1

The time required to evacuate a given system from initial pressure to final pressure is related to the pumping speed by Equation 1.

$$t = \frac{2.3\ V}{S} \log_{10} \frac{p_1}{p_2} \qquad (1)$$

where

$t$ = time required to evacuate system.
$V$ = volume of system.
$S$ = pumping speed.
$p_1$ = initial pressure.
$p_2$ = final pressure.

Equation 1 holds true if the initial and final pressures lie within the range at which the pump is designed to operate. Equation 1 is used in Example A to calculate pumping speed.

**EXAMPLE A: CALCULATION OF PUMPING SPEED**

Given: A mechanical pump operates at a speed of 100 liters/s, over the pressure range from 760 torr to 1 torr.

Find: Time required for this pump to evacuate a 50-liter chamber from atmospheric pressure to 1 torr.

Solution: Use Equation 1:

$$t = \frac{2.3\ V}{S} \log_{10} \frac{p_1}{p_2}$$

$$= \frac{(2.3)(50)}{100} \log_{10} \frac{760}{1}$$

$$t = 3.3 \text{ seconds}$$

In practice, pumps are connected to the vacuum chamber through pipes or other channels, through which the gas must flow. The pipe also will affect the rate of gas removal. The effect of the pump is expressed in terms of a parameter called "conductance." Conductance for a channel is defined as "the flow of gas molecules through the channel per unit time, divided by the pressure difference between the ends of the channel." Mathematically, conductance can be expressed by Equation 2.

$$C = \frac{p_1 V_1}{(p_1 - p_2)} \tag{2}$$

where

$C$ = conductance in volume/time.

$V_1$ = volume of gas (at initial, inlet pressure $p_1$) that moves through the channel per unit time.

The product $p_1V_1$ is, from the ideal gas law, a measure of the quantity of gas so moved, per second.

The reciprocal of the conductance is called the "impedance" and is given by Equation 3.

$$Z = \frac{1}{C} \tag{3}$$

where

$Z$ = impedance.

Notice the analogy between Equations 2 and 3 and resistance and its reciprocal in the electrical system. Thus, two pipes with impedance $Z_1$ and $Z_2$ connected in series have total impedance $Z_T$ indicated by Equation 4.

$$Z_T = Z_1 + Z_2 \tag{4}$$

For the same two pipes connected in parallel, the total impedance $Z_T$ is given by Equation 5.

$$\frac{1}{Z_T} = \frac{1}{Z_1} + \frac{1}{Z_2} \tag{5}$$

Equations 4 and 5 are exactly similar to the equations for the electrical resistance of two resistors.

Determination of conductance in a practical case can become complicated. The exact value of conductance depends upon the shape of the pipe, the average pressure, and the dimensions of the pipe, in a complicated fashion. Only one valid relation in relatively low pressure regimes (pressure $< 10^{-2}$ torr) is presented here; in this region, for a circular pipe, Equation 6 applies.

$$C \simeq \frac{12\ d^3}{\ell} \tag{6}$$

where

$C$ = conductance in liters/s.
$d$ = diameter of pipe in cm.
$\ell$ = length of pipe in cm.

The effect of the pipe's conductance $C$ on the pumping speed of the total system is given by Equation 7.

$$\frac{1}{S_T} = \frac{1}{S} + \frac{1}{C} \tag{7}$$

where

$S_T$ = pumping speed of total system (pump plus pipe).
$S$ = pumping speed of pump alone.

This equation implies that the pumping speed of the system cannot be greater than the speed of the pump or of the conductance of any of the pipes in the system. Equation 7 is used to solve a problem in Example B.

**EXAMPLE B: CALCULATION OF PUMPING SPEED**

Given: The pump of Example A is connected to the chamber of volume 50 liters by a pipe of 40 liters/second conductance.

Find: Time required to pump the chamber down from 760 torr to 1 torr.

Solution: The total pumping speed $S_T$ is given by Equation 7:

$$\frac{1}{S_T} = \frac{1}{100} + \frac{1}{40} = 0.035$$

$$S_T = 28.6 \text{ liters/s}$$

When this new total pumping speed is substituted into Equation 1, the result is the following:

$$t = \frac{2.3\ V}{S} \log_{10} \frac{P_1}{P_2}$$

$$= \frac{2.3 \times 50}{28.6} \log_{10} \frac{760}{1}$$

$$t = 11.6 \text{ seconds}$$

## TYPES OF VACUUM PUMPS

Many different types of vacuum pumps are in use, including these four common types:

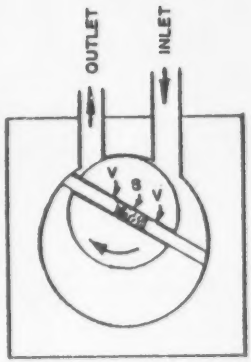
- The rotary mechanical pump.
- The diffusion pump.
- The sputter-ion pump.
- The cryogenic pump.

Each type is designed for a range of pressures for which it is effective. Only the rotary mechanical pump exhibits a range that includes atmospheric pressure. Thus, a common situation involves use of a mechanical pump plus a second pump; for example, a diffusion pump. The mechanical pump reduces the pressure from 760 torr down to the lower limit of its operating range, usually in the middle-vacuum range. Then the diffusion pump is switched on. It is effective in the middle-vacuum range and pumps the system down to a lower final pressure.

## ROTARY PUMPS

Rotary mechanical pumps rely upon the motion of internal structures in the pump. In such pumps, during a cycle of its rotation, gas from the vacuum system is trapped, compressed, and moved from the lower-pressure inlet to the high-pressure outlet. Gas then is expelled to the atmosphere.

Figure 2 is a diagram of a typical rotary mechanical pump. This design is a common one employed in many commercial pumps, particularly in smaller pumps. There are other designs for mechanical pumps, but the basic features of mechanical pumps can be understood with reference to Figure 2.




V - VANE

S - SPRING

FIG. 2

The circular rotating element, or rotor, is driven by an electric motor. The rotor is inside a larger circular area within the pump body. The rotating element is off center, as shown, so that one side always is in contact with the interior wall. The empty volume is crescent-shaped, as shown. The rotating element has two vanes that are forced outward by a spring. The vanes maintain contact with the walls throughout the rotation of the rotor.

Oil lubricates the rubbing surfaces and seals the interfaces, in order that gas cannot flow past the ends of the vanes.

Gas enters the pump from the chamber through the inlet. Figure 3 illustrates stages in the rotation cycle of the rotor. In Figure 3a, gas enters the pump. In Figure 3b, the vane has passed the inlet and the gas is trapped. The volume available to the trapped gas is reduced, and the gas is compressed (Figure 3c). In Figure 3d, the volume has become very small, and the gas is expelled throughout the outlet. Meanwhile, more gas has entered through the inlet for another cycle.

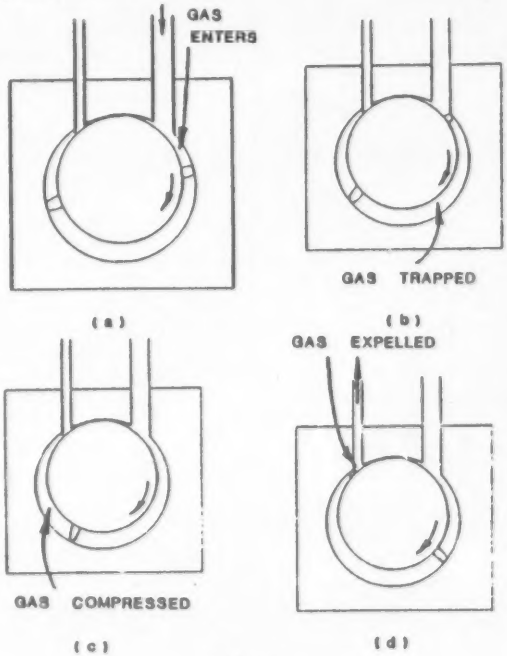



FIG. 3

Rotary mechanical pumps are effective over a pressure range of from 760 torr down to a lower limit of about $5 \times 10^{-3}$ torr. Thus, they can be used as the first stage in a multi-pump system. The mechanical pump reduces the pressure from atmospheric pressure down to the lower limit of its operating range. Then a second

pump, capable of reaching lower pressures, is switched on and further reduces the pressure.

The pumping speeds of available mechanical rotary pumps vary over a wide range, from small units having speeds of less than 1 liter/second, driven by 1/8-horsepower motors, up to units with pumping speeds of over 300 liter/second, driven by 40-horsepower motors.

## DIFFUSION PUMPS

Diffusion pumps remove gas by forming a high velocity jet of vapor from oil or mercury evaporated in the low pressure produced by a mechanical pump. The high-velocity jet carries the gas molecules along with it to the discharge port that leads to the mechanical pump.

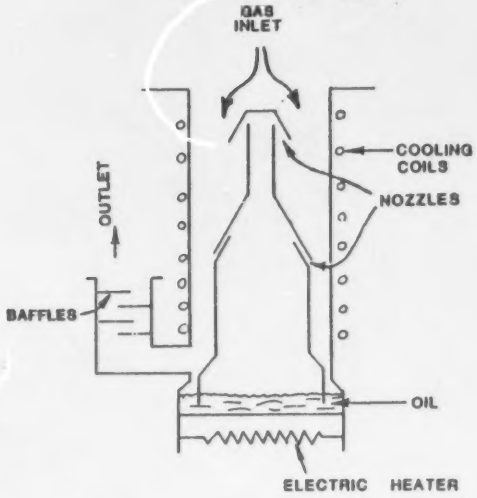



FIG. 4

A diffusion pump is illustrated in Figure 4. The outlet is connected to a mechanical pump that exhausts the pumped gas to the atmosphere. The pump shown is an oil diffusion pump, but mercury may be used instead. The oil is evaporated by the heater. It passes upward in the central part of the pump and emerges through the nozzles. As the oil vapor passes through the nozzles, it is deflected downward and carries gas molecules that enter through the inlet along with it. The oil is recovered by condensation on the pump walls, usually cooled by water running through coils wrapped around the pump. The gas emerges from the outlet, where baffles trap any remaining oil vapor. Figure 4 displays two stages of nozzles, but diffusion pumps with more stages are common.

Diffusion pumps require a pressure below one atmosphere to begin operation; therefore, they always are used in conjunction with a mechanical pump. The mechanical pump reduces the pressure to about 0.1 torr or so, at which pressure the diffusion pump can begin operation. The diffusion pump then can reduce the pressure much further. The lower limit of operating pressure for diffusion pumps is in the range from $10^{-6}$ to $10^{-9}$ torr, depending upon the design.

The pumping speeds offered by diffusion pumps cover a wide range, depending upon size and type of construction. Diffusion pumps with speeds ranging from 1 liter/second to many thousands of liters/second are available.

All diffusion pumps suffer, to some extent, from a back-streaming of the oil vapor into the vacuum chamber, which leads to contamination of the chamber by the oil. To minimize this, cold traps and baffles are placed between the pump and the chamber. Such baffles increase the probability that an oil molecule will strike a cold surface and condense before making its way into the vacuum chamber.

## SPUTTER-ION PUMPS

In sputter-ion pumps, the gas is removed from the vacuum chamber volume by being trapped on the surfaces of electrodes within the pump. The gas is not expelled, but retained within the pump. The gas molecules are trapped, both by chemical reactions with a reactive metal that forms the electrodes, and also by being buried under newly-sputtered layers of metal. The metal most commonly used for sputter-ion pumps is titanium, which is highly active chemically.

A schematic diagram of the structure of a sputter-ion pump is shown in Figure 5. A voltage of several kilovolts is applied between the anode and the cathode, supporting an electrical discharge in the low-pressure gas. Positive ions of the gas molecules are produced in the discharge. These ions are accelerated to the cathode; they strike the cathode with high velocity and are buried within the cathode. The impact of the high-velocity ions drives titanium atoms from the surface of the cathode; that is, it "sputters" titanium atoms. The reactive titanium atoms react chemically with gas molecules and then settle on the walls of the pump. The gas molecules, thus, are effectively removed. The magnet of Figure 5 causes the electrons in the electrical discharge to move in spiral paths and increases the probability of ionization for gas molecules. The magnetic field typically is about 3000 Gauss.

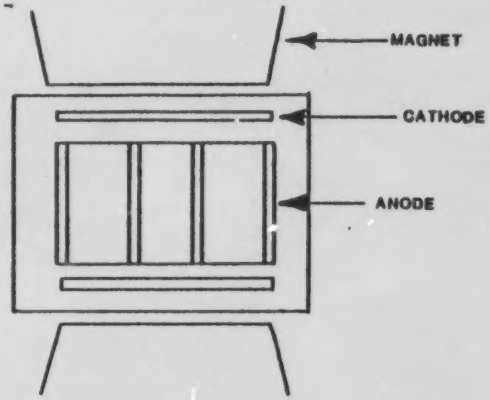



FIG. 5

The titanium ion pump is very effective for chemically-active gases, such as oxygen, nitrogen, and hydrogen. It is less effective for inert gases, especially for argon, which is removed only with difficulty by such a pump.

Sputter-ion pumps are desirable when a system free from oil vapor is desired. They are entirely free from such contamination.

Because the trapped gas builds up on the pump walls, the total capacity of such a pump is limited. Sputter-ion pumps must be cleaned periodically to remove the gas entrapped on the walls. In order to limit the total amount of gas that must be trapped, they are started only at low pressure, $10^{-2}$ torr or less. They, too, also are used in conjunction with a mechanical pump, which reduces the pressure to the range at which the sputter-ion pump is effective. Then the sputter-ion pump is started. Final gas pressures as low as $10^{-10}$ torr can be obtained with available pumps of this type. Sputter-ion pumps with pumping speeds ranging from 10 liters/second to $10^5$ liters/second are available. They offer an effective and clean method of reaching the ultrahigh vacuum region.

## CRYOGENIC PUMPS

In cryogenic pumps, a surface is held at very low temperature by contact with liquid nitrogen (temperature 77 K) or liquid helium (temperature 4 K). Other gases striking the surface will be condensed and trapped on it. As is the case with sputter-ion pumps, the gas is not expelled from the system, but trapped. When the surface is allowed to warm, the trapped gas will be released.

Cryogenic pumps are first evacuated to a pressure of $10^{-2}$ torr, or below, by a mechanical pump. They must begin operation at relatively low pressure, both to preserve the coolant and to prevent the formation of too thick a layer of condensed gas on the surface. Thus, the cryogenic pump should not be operated at pressures greater than $10^{-2}$ torr.

Cryogenic pumps are capable of reaching very low pressures: Systems capable of reaching $10^{-14}$ torr have been developed. The pumping speed can be high, with commercially-available units offering pumping speeds up to 5000 liters/second.

## VACUUM SYSTEMS

The pump is only one component, although an important one, in a complete vacuum system. In addition to the pump, the system will contain components such as tubes, baffles, cold traps, valves, and vacuum gages. (The gages used to measure vacuum levels are described in Module 10F5.)

The materials from which the vacuum system is constructed are important. They must be materials having low vapor pressure. The lowest pressure that a vacuum system can reach is equal to the vapor pressure of the materials from which it is made. The materials also must possess mechanical strength sufficient to withstand the pressure difference between the inside and the outside of the system. For adequate strength, the walls of the vacuum chamber must be reasonably thick. Also, the materials should have the capacity to be easily cleaned.

To satisfy these requirements, vacuum systems are constructed either of glass or of metal. Stainless steel often is utilized because of its resistance to corrosion; but when cost is an important consideration, aluminum or brass may be used. For ultrahigh vacuum work, stainless steel almost always is the choice.

For lubrication of moving parts, some vacuum greases that have vapor pressures as low as $10^{-8}$ torr are available. For ultrahigh vacuum work, all greases and waxes are to be avoided.

The materials of the system must be cleaned carefully to avoid release of gases trapped on the surface. After assembly, the system often will be baked while pumping at temperatures ranging up to 400°C, to remove entrapped gases.

In systems using diffusion pumps, the backstreaming of oil molecules into the vacuum chamber is undesirable. Baffles and cold traps may be used to reduce this flow. Baffles are designed to ensure that any molecule moving back toward the chamber must strike at least once on a surface. The surfaces may be water-cooled to aid condensation of the oil on the surface.

Cold traps are cooled by liquid air. Gas passing through a cold trap must make at least two right-angle turns. Oil vapor striking the cold surfaces will condense.

Valves frequently are used to isolate portions of a vacuum system. This technique often is employed when two pumps are used to evacuate a system. Suppose, for example, that both a mechanical pump and a sputter-ion pump are employed to evacuate a particular chamber. When the chamber is allowed to refill with air, the sputter-ion pump may be sealed off behind a valve and allowed to remain in vacuum. When the system is evacuated again, it is first pumped by the mechanical pump. When the limiting pressure of the mechanical pump is reached, the valve is reopened and the sputter-ion pump further reduces the pressure. This technique allows more efficient use, and less contamination of, the sputter-ion pump.

## APPLICATIONS OF VACUUM

Vacuum technology has many applications in science and industry. Most scientific laboratories routinely use vacuum equipment to conduct research in areas such as electrical conduction in low-pressure gases, plasma physics, electron microscopy, and ultraviolet spectroscopy.

In more routine applications, vacuum equipment is used in industrial production for many purposes. Light bulbs first are evacuated, then refilled with an inert gas to increase their lifetime. Electronic tubes must be evacuated to provide reasonably long paths for the electrons traversing the tube. The electron tubes used in the control and amplifier circuits of TV sets and picture tubes alike depend upon vacuum technology.

Since vacuum provides good resistance to heat flow, double-walled flasks, with the space between the walls evacuated, possess good thermal insulation. This property is used in thermos bottles to keep food warm or cold.

Many foods are vacuum processed to remove humidity: Products such as freeze-dried coffee, fruit juice, and condensed milk are produced with the aid of vacuum technology.

Metals evaporated within a vacuum system produce reflective coatings on many different items. Plastic toys and jewelry are coated with a thin film of aluminum for decorative purposes. The aluminum is evaporated from tungsten filaments heated electrically. When the vaporized metal strikes a surface, it deposits on the surface and gradually builds up a reflective layer. Such operations generally are carried out at a pressure of about $10^{-3}$ or $10^{-4}$ torr. Vacuum deposition of metals probably is the largest single use of vacuum technology in industry.

The range of applications described above represent only a few of the areas in which vacuum technology is important.

## SUMMARY

A number of different pumps are used as energy converters to produce a vacuum in enclosed chambers. These pumps include rotary mechanical pumps, diffusion pumps, sputter-ion pumps, and cryogenic pumps. The pressure ranges that can be covered vary from one pump type to another. In common practice, a mechanical pump is used to pump down from atmospheric pressure to medium vacuum; and then a second pump is switched on to reach high or ultrahigh vacuum.

A pump for reducing pressure in a chamber may be characterized by its pumping speed. The pumping speed measures the rate at which gas is removed by the pump. It has units of volume per unit time; for example, liter/second. The definition of pump speed is the volume of gas per unit of time removed from the system at the pressure existing at the inlet to the pump.

## VACUUM PUMP EVACUATION OF VACUUM CHAMBER

### PROCEDURE

Vacuum system, including:
- Mechanical pump.
- Either a diffusion pump or a sputter-ion pump.
- Vacuum gages; for example, a mechanical gage plus a thermocouple gage and an ionization gage (or other equivalent combinations).
- Valves between the pumps and the chamber to be evacuated.
- Flanges, pipes, coupling, as required.

A clock or watch with which to measure time.
Semilogarithmic graph paper.
Stopwatch or lab timer.

### MATERIALS

The student will learn to use vacuum pumps and will use at least two different pumps to evacuate a vacuum system. The vacuum system will be assumed to be available. The student is not requested to set up a vacuum system since that is beyond the scope of this module.

The pressure will be monitored during pump down by vacuum gages, the operation of which is assumed to be known from Module 10F5. Familiarity with the use of a mechanical gage, of a thermocouple gage, and of an ionization gage is assumed. Other gages may be substituted.

A sketch of a system is presented in Figure 6. The first pump is a mechanical one. The second pump may be either a diffusion pump or a sputter-ion pump. In systems where the mechanical pump pumps through a diffusion pump, the procedure will be varied accordingly. (See instructor.)

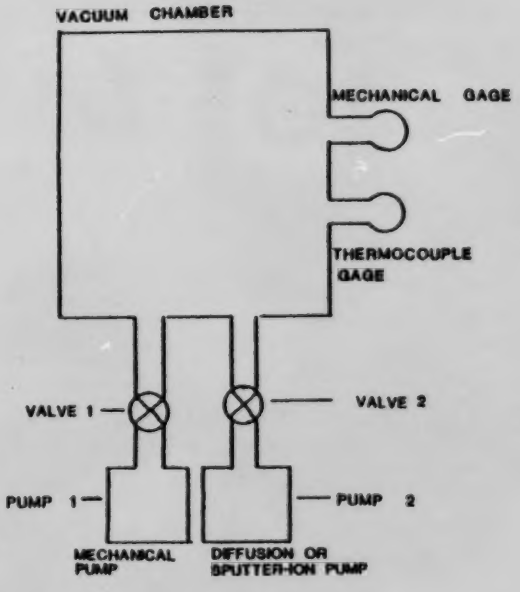



FIG. 6

1. Open valve 1, and close valve 2.

2. Turn on mechanical pump.

3. Observe pressure on the mechanical gage, and record in Data Table the pressure at various times after pump is started.

4. When pressure range appropriate to thermocouple is reached, turn on the thermocouple gage. (See Module 10F5.) Record pressure versus time.

5. When pressure has stopped decreasing, record ultimate pressure reached by mechanical pump.

6. CAUTION: Some precautions are necessary to prevent overheating of a sputter-ion pump if one is being used. Valve 2 must be opened very slowly. If sputter-ion pump begins to overheat, close valve again, and allow it to cool. Now close valve 1, and open valve 2. Start pump 2.

7. With the ionization gage, measure pressure in system at various times after pump is turned on.

8. Record ultimate pressure reached by system.

9. Plot pressure versus time from Steps 7 and 8. The plot may be made on semilogarithmic graph paper.

10. From plot, choose two values of pressure, and measure time required for the pump to reduce the pressure from the higher value to the lower value.

11. Measure and record dimensions of chamber and of pipe.

12. From Steps 10 and 11, calculate pumping speed of the system (pump plus pipe). Use Equation 1.

13. Calculate conductance of the pipe (Equation 6), and then calculate pumping speed of pump (Equation 7). Compare result with manufacturer's specified pumping speed. Is there a difference between the result and the specified speed? If so, why?

**DATA TABLE**

| TYPE OF PUMP | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Mechanical | | | Diffusion or Sputter-ion | | | | | | | | |
| Time Interval | Pressure | Ultimate Pressure | Time Interval | Pressure | Ultimate Pressure | Time required to pump from 1st pressure to 2nd (from plot) | Dimensions: Vacuum Chamber | Dimensions: Pipe | Pumping Speed of System | Conductance of Pipe | Pumping Speed of Pump |
| | | | | | | The two plotted pressures:<br>1. _____<br>2. _____ | | | | | |
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## SELF CHECK

1. Define the following terms:

   Pumping speed.
   Pump-down time.
   Conductance for flow of gas through a pipe.
   Impedance for flow of gas through a pipe.

2. A pump has a pumping speed of 100 liter/second. How much time will be required for that pump to reduce the pressure in a 100-liter chamber from 1 torr to $10^{-5}$ torr?

3. A pipe has a diameter of 5 centimeters and a length of 50 centimeters. What is the impedance of the pipe, when the pressure is $10^{-3}$ torr?

4. Describe the operation of the following pumps:

   Rotary mechanical pumps.
   Diffusion pumps.
   Sputter-ion pumps.
   Cryogenic pumps.

5. State the approximate pressure range covered by each of the above pump types.

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Dushman, S. Scientific Foundations of Vacuum Techniques. New York: John Wiley & Sons, Inc., 1949.

LaPelle, R. R. Practical Vacuum Systems. New York: McGraw-Hill Book Co., 1972.

Roth, A. Vacuum Technology. Amsterdam: North Holland Publishing Co., 1976.

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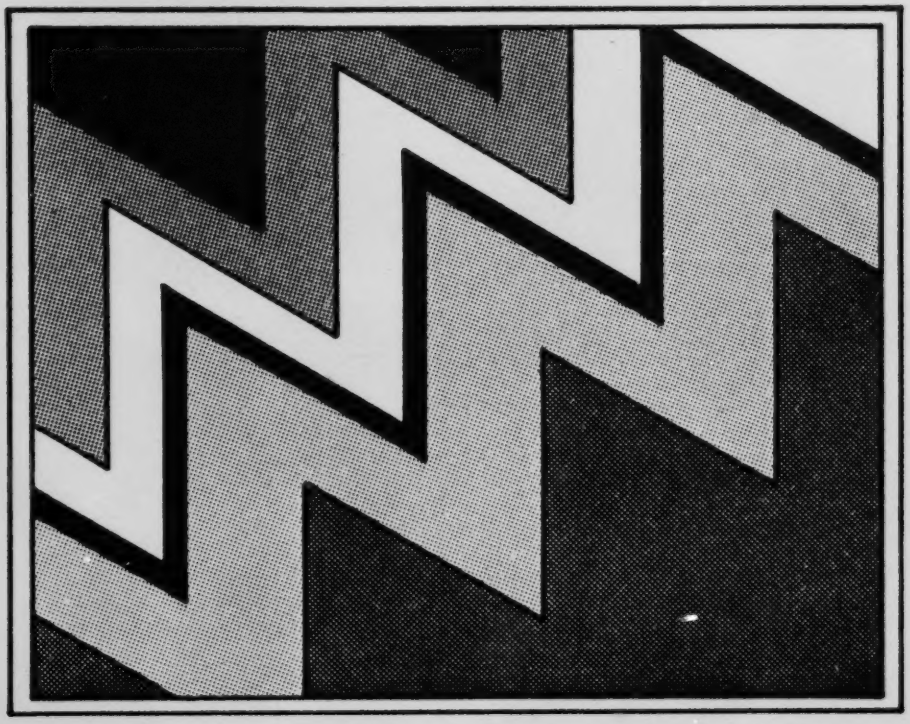
UNIFIED TECHNICAL CONCEPTS

MODULE 9 E 1

ELECTRIC GENERATORS



ELECTRICAL APPLICATION OF ENERGY CONVERTORS

Technical Education Research Center - Southwest

TERC - SW

## INTRODUCTION

The conversion of mechanical energy into electrical energy is perhaps the most significant form of energy conversion. Today's technological society depends greatly upon the ability to generate, transport, store and utilize electrical energy. An electric generator is an energy converter that changes rotational mechanical energy to electrical energy. This module presents the theory of operation and basic design of d.c. generators. In the laboratory, the student will operate a d.c. generator and will measure the electrical power it produces.

## PREREQUISITES

Student should have completed Concept Module 9-0, "Energy Converters," and Application Module IE4, "Magnetic Forces and Fields."

## OBJECTIVES

Upon completion of this module, the student should be able to:

- Use the right-hand generator rule to determine the direction of force on electrons in a conductor moving through a magnetic field.
- Determine the direction of electron flow, given a diagram of a loop of wire rotating in a magnetic field.
- List the three factors that determine the magnitude of the voltage produced by a genrator.
- Draw and label sketches showing the differences in d.c. and a.c. generators and the wave forms produced by each.
- State two methods commonly used to produce the magnetic field in generators.

- Given the appropriate equipment, operate a d.c. generator, and measure the electrical power produced.

## DISCUSSION

The magnetic force acting on an electric charge moving through a magnetic field was discussed in Application Module 1E4, "Magnetic Forces and Fields." This module describes the application of these forces in generation of electric currents.

Figure 1 illustrates the right-hand generator rule used to predict the direction of force on an electron in a wire. The forefinger points in the direction of the magnetic field. The middle finger points in the direction of motion of the conductor. The thumb points in the direction of the force (or thrust) on the electron and, thus, the direction of electron flow in the wire.

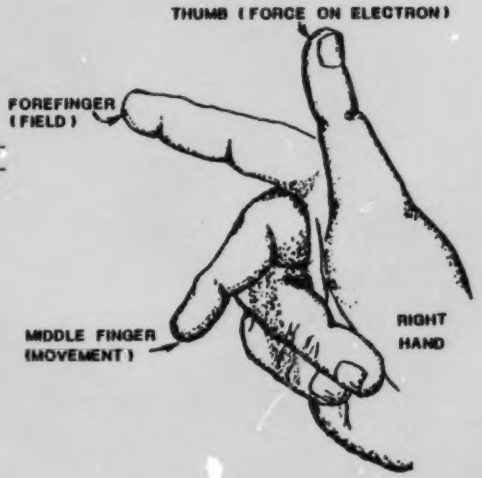
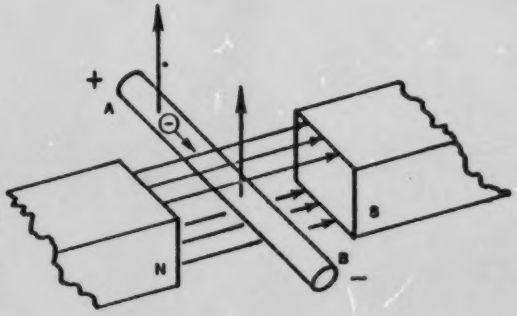



FIG. 1

Figure 2 shows the application of this rule to a straight piece of wire moving through a uniform field between two magnetic poles. In Figure 2a the field is to the right and the wire moves upward. Magnetic force moves electrons in the wire from A toward B, resulting in a potential difference across the wire as shown. In Figure 2b the conductor moves downward, reversing the direction of force on the electron and the polarity of the voltage across the wire.

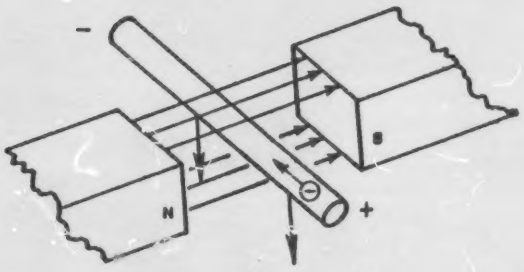
In Figure 2c the conductor moves along lines of magnetic force, in which case charged particles in the wire do not cross magnetic-field lines; and there is no force on the electron. Thus, no voltage is present across the conductor.

Figure 2d shows the results when the conductor moves at an angle other than perpendicular or parallel to the field lines. In this case, the vertical component of the motion produces a force on the electron just as the vertical motion in Figure 2a. The horizontal component produces no force on the electron.

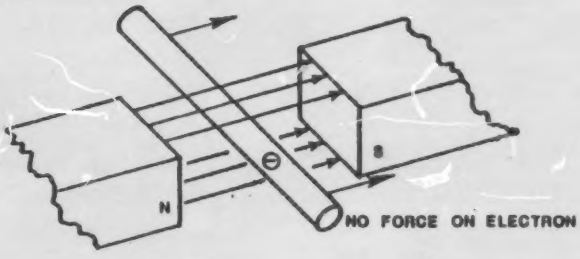



(a)

Figure 3 shows how this effect is applied in a d.c. electric generator. This generator consists of a square




(b)

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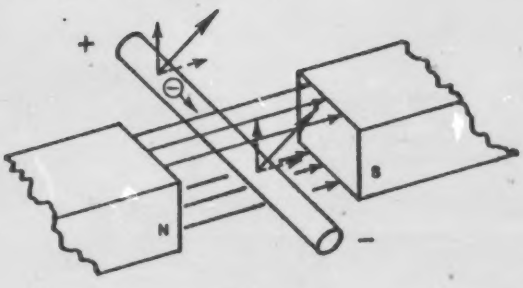
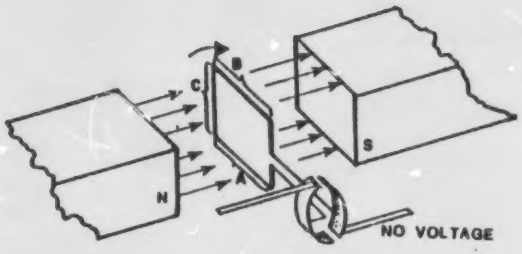
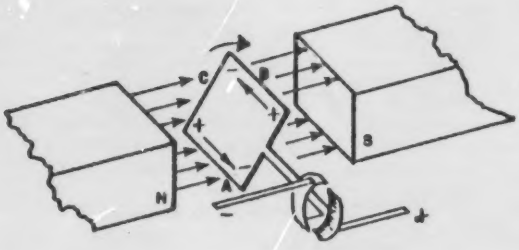



(d)

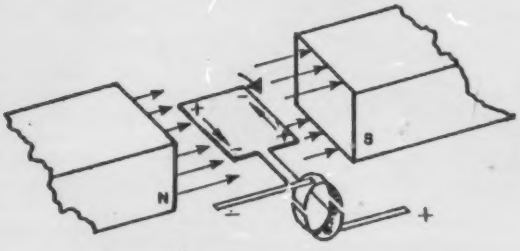
FIG. 2



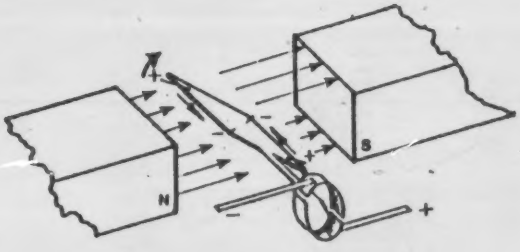

(a)




(b)




(c)




(d)

FIG. 10

loop of wire rotating in a fixed magnetic field and of a split ring commutator.

In Figure 3a, the upper output contact (called a brush) is connected to wire segment A. At this time, both wire segments are moving parallel to the magnetic-field lines, and no voltage is generated. This position is point a on the graph in Figure 4. This graph shows the voltage across the generator brushes as a function of time.

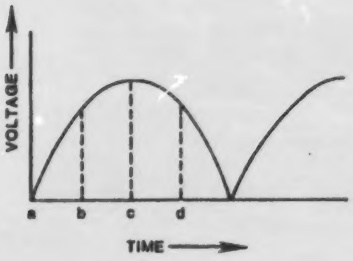



FIG. 4

Figure 3b shows the position of the loop some short time later. Wire segments A and B are now moving at an angle to the magnetic-field lines, and a voltage is being produced in sides A and B. Side B is moving downward through the field, causing a force on the electrons in the direction indicated by the arrow. Side A moves upward, resulting in a force in the opposite direction. These two voltages add in series to produce the output voltage shown as point b in Figure 4. Wire segment c contributes no voltage, because it crosses no magnetic field lines as it moves.

In Figure 3c, the two voltage-producing wire segments are moving perpendicularly to the direction of the magnetic field. This position produces the maximum voltage, indicated by point c in Figure 4.

In Figure 3d, the motion of the wire segments is no longer perpendicular to magnetic field lines, and the output voltage has dropped to that indicated by point d in Figure 4. When the loop reaches the vertical position again, the voltage will be zero. Each brush will slip to the other segment of the commutator ring, and the entire process will be repeated.

The amount of voltage present across the wire segment depends upon the strength of the magnetic field and the velocity of the segment perpendicular to the field. This voltage is small for practical fields and velocities. Generation of usable voltage requires a rotating coil of many loops, shown schematically in Figure 5. As this coil rotates, a voltage is produced across each horizontal wire segment. All these voltages add in series to produce the total output voltage of the generator. This output is shown as a function of time in Figure 6. The amplitude (height or maximum voltage) of this curve is determined by three factors:

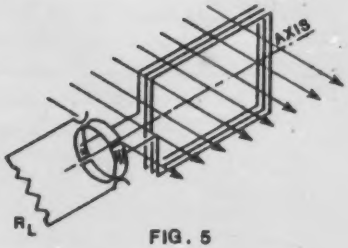



FIG. 5

- Number of loops in the moving coil.
- Strength of the magnetic field.
- Rotational rate of the coil.

When any one of these factors is increased, output voltage also increases. If the rotational rate is increased, the frequency at which the output varies is also increased.

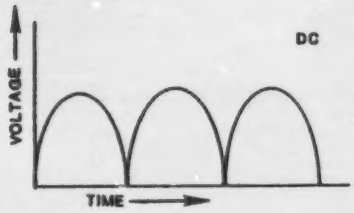



FIG. 6

If the same generator is equipped with a pair of slip-ring contacts as shown in Figure 7, an a.c. voltage will be produced. The output of such a generator, often called an "alternator" because it generates an alternating current, is shown in Figure 8.

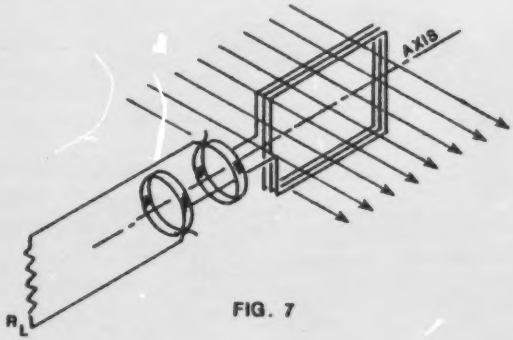



FIG. 7

Permanent magnets often are used to provide the magnetic field in small generators, but larger units require fields of greater strength than those available from permanent magnets. Figure 9 shows how this problem is solved in most generators. A d.c. current flows through a stationary field coil to produce a magnetic field. A multipole armature, shown in Figure 10, is rotated in this magnetic field to produce the output voltage. This armature consists of several coils of wire, each connected to two opposing segments of the commutator. This arrangement allows only the maximum voltage portion of the voltage-versus-time curve of each coil to be connected to the generator output. The resulting output voltage is shown in Figure 11.

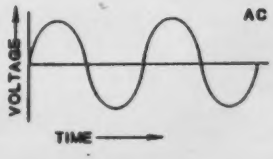



FIG. 8

When a generator is turning with a load connected to the output, the current flowing in the load circuit is also flowing in the armature. Such current establishes a magnetic field around the armature; this field opposes the fixed magnetic field of the generator. The interaction of these two magnetic fields, one fixed and one rotating, opposes the rotation of the armature; therefore, rotational mechanical energy must be supplied to the armature to maintain its rotation. Thus, the armature of a generator rotates easily if no load is attached, but requires greater torque as the current delivered increases. This situation is required by the principle of the conservation energy. The maximum current that may be produced by a generator is limited by the size of wire used in the armature.

The most important application of d.c. generators arises from the fact that d.c. electric motors allow finer speed control than either a.c. motors or engines that derive their power from the combustion of chemical fuels. In locomotives and ships, diesel engines

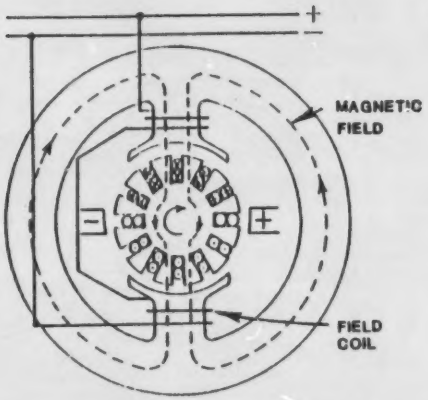



FIG. 9

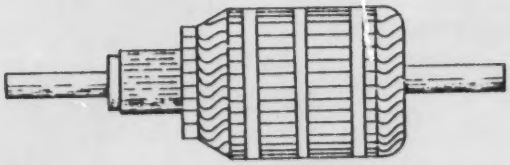


FIG. 10

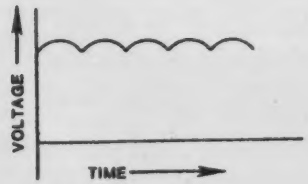



FIG. 11

or steam turbines drive d.c. generators; electrical output power then is used to operate d.c. motors that provide propulsion.

## SUMMARY

Electric generators (and alternators) convert rotational mechanical energy into electrical energy. Magnetic forces and fields make the operation of generators possible.

## GENERATOR OPERATION AND CHARACTERISTICS

### MATERIALS

Demonstration motor-generator (Sargent-Welch #2469 or equivalent).
Two variable d.c. power supplies, 0-6V, 5A with meters to indicate output current and voltage.
d.c. voltmeter, 0-25V.
d.c. milliammeter, 0-500 mA.
Single-pole, single-throw switch.
Wire for connectors.
10 Ω, 1W resistor.

### PROCEDURE

1. Set up equipment as shown in Figure 12.

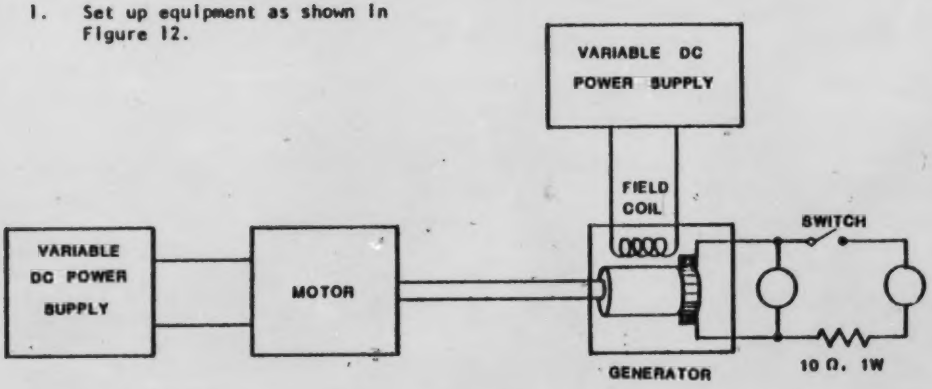



FIG. 12

2. Turn on d.c. power supply connected to motor, and set voltage to produce a moderate motor speed.

3. With switch open, turn on d.c. power supply connected to generator field coil, and set voltage at approximately 3V.

4. Measure output voltage of generator. Record field-coil voltage, output voltage of generator, motor voltage and motor current in Data Table.

5. Increase field-coil voltage to 6V, and repeat step 4.

6. Using input voltage of motor as in step 2, close switch.

7. Repeat entire procedure, recording all data as before with addition of output current of generator.

8. Determine input power of motor and output power of generator from P = I V and complete Data Table.

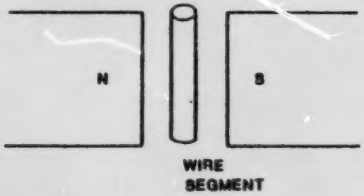
9. Why is more power required to turn a larger generator (or one with larger windings) than to turn a smaller one?

| DATA TABLE | | | | | | |
|---|---|---|---|---|---|---|
| NO LOAD | | | | | | |
| Motor | | | Generator | | | |
| Voltage (V) | Current (A) | Power (W) | Field coil voltage (V) | Output voltage (V) | | |
| | | | | | | |
| LOAD | | | | | | |
| Motor | | | Generator | | | |
| Voltage (V) | Current (A) | Power (W) | Field coil voltage (V) | Output voltage (V) | Output current (MA) | Output power (W) |
| | | | | | | |

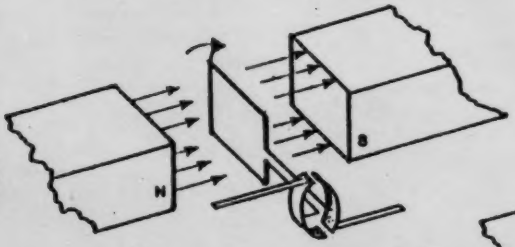
## SELF CHECK

1. Determine the direction of force on electrons in the wire at the right if the wire moves

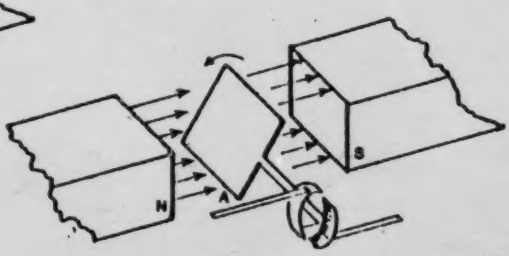
   a. Out of the page toward the reader.
   b. Toward the south pole of the magnet.



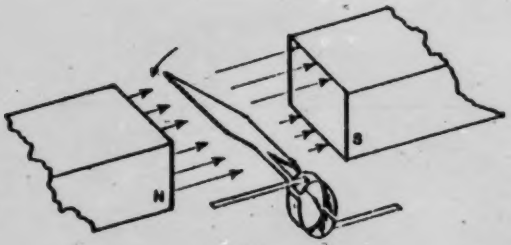

2. Indicate the direction of electron flow through the generator coil in the following diagrams. (Use the right-hand generator rule for electron flow presented in the text.)




(a)




(b)




(c)

3. List the three factors that determine the voltage produced by a generator.

4. Sketch the output waveforms from an a.c. generator and a d.c. generator.

5. State two methods of producing magnetic fields in generators.

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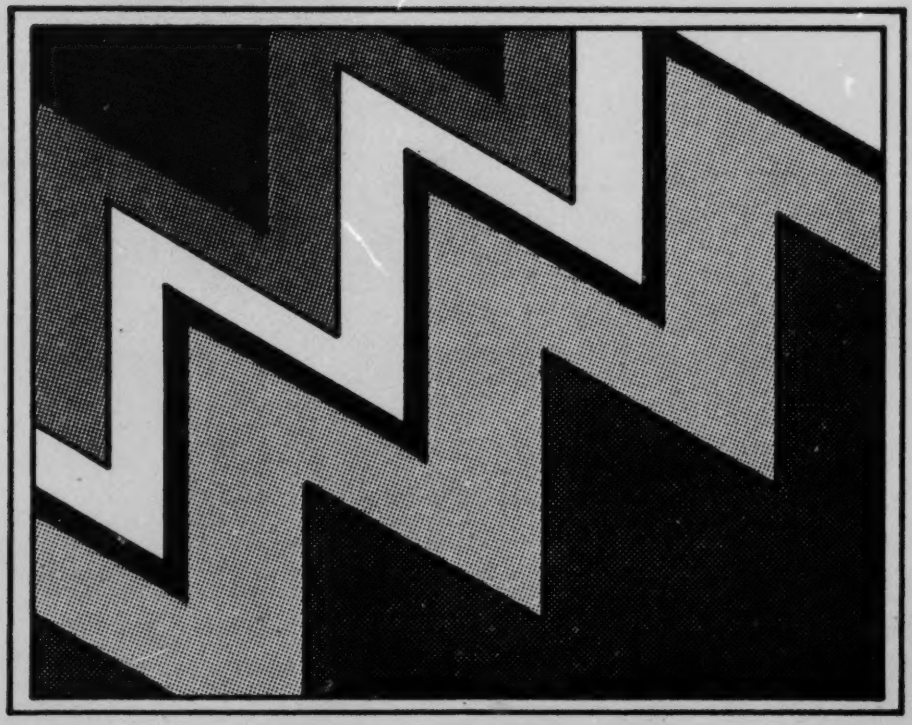
UNIFIED TECHNICAL CONCEPTS

MODULE 9 E 2

ALTERNATORS



ELECTRICAL APPLICATION OF ENERGY CONVERTORS

Technical Education Research Center - Southwest

TERC - SW

## INTRODUCTION

Generator principles discussed in Module 9E1, "Electric Generators," apply to alternators as well as to d.c. generators; both convert mechanical energy into electrical energy. Alternators produce an a.c. waveform and are used in power-generating plants to provide large quantities of electrical energy for home and industrial uses. Rectifying diodes are used to produce d.c. voltage with an alternator. Automobile alternators convert rotational mechanical power to d.c. voltage and current by this means. This module presents the theory, construction details, and applications of alternators. In the laboratory, the student will determine the output power and efficiency of an alternator.

## PREREQUISITES

Student should have completed Concept Module 9-0, "Energy Converters," and Application Module 9E1, "Electric Generators."

## OBJECTIVES

Upon completion of this module, the student should be able to:

- Explain with the use of diagrams how an alternator produces an a.c. voltage.
- Draw and label diagrams showing the construction of the rotor of an alternator having several pole pairs. Include the electrical windings, rotor shell, brushes, and slip-rings.
- Given any two of the following quantities, calculate the third:

  Number of pole pairs.
  Rotational rate in revolutions per second.
  Output frequency.

- State two major advantages of alternators over generators

for the production of electrical power.

- Given the number of pole pairs in the rotor of a three-phase alternator, determine the total number of coils in the stator; and explain how they are connected.

- Given the appropriate equipment, measure the efficiency of an automobile alternator; and observe the output waveform.

## DISCUSSION

A review of the electrical generator principle (Module 9E1) will help in the understanding of alternator operation. Recall that to generate electrical energy from mechanical energy, relative motion must exist between a magnetic field and a conductor. When alternators are used to generate electrical energy, the magnet moves in a rotary motion about a fixed coil. All the rules discussed in Module 9E1 for electrical generators also apply to alternators.

Figure 1 shows a magnet that rotates inside a coil to produce voltage. The direction of induced voltage at successive points of rotation is shown in Figure 2. The direction of induced voltage is the same as the direction of conventional current flow. Note that in Figure 2a the rotating magnetic field is not cutting the coil, and that no voltage is induced, therefore, into the coil at this point. During the first quarter turn, the voltage increases and reaches a maximum as the poles of the magnet pass the coil of wire and decreases during the next quarter turn. In Figure 2d, the magnet has rotated a full 180°, or one-half turn, and the induced voltage is again zero. The direction of current flow in the coil can be determined by the left-hand generator rule and is shown by

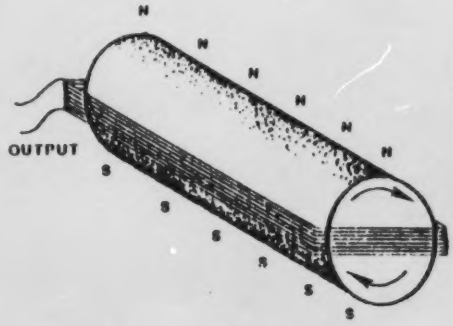



FIG. 1

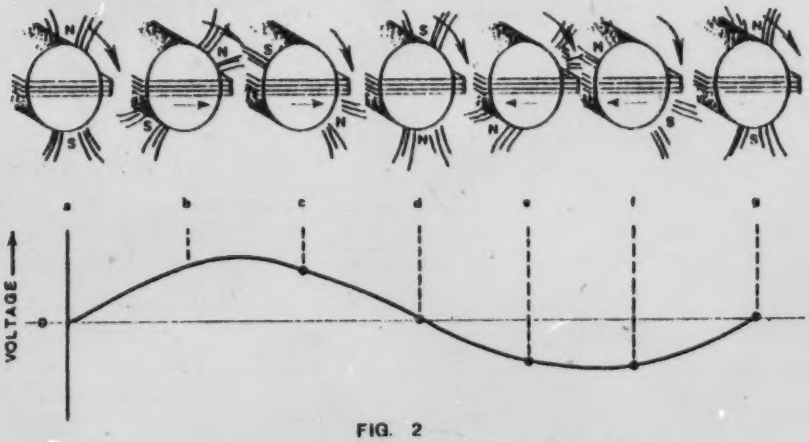



FIG. 2

the arrows.

One complete rotation of the magnet produces one cycle of induced alternating voltage, as shown. When the magnet is rotated at a rate of 3600 revolutions per minute, or 60 revolutions per second, the frequency of the waveform produced is 60 cycles per second, or 60 Hz. The angular velocity of the rotating magnet in industrial alternators is very closely controlled, to maintain the exact frequency of 60 Hz, which is the standard frequency of the a.c. voltage used in homes and industry.

Magnets having four or more poles generally are used in industrial alternators. Since there are more pairs of poles producing magnetic fields cutting the coils of wire, more complete waveforms of a.c. voltage are produced for each rotation of the rotor. The relationship between number of magnetic pole pairs, frequency, and angular velocity of the rotating magnet is expressed by Equation 1.

$$f = N\omega \qquad (1)$$

where

$f$ = frequency of induced voltage in Hz.
$N$ = number of pole pairs.
$\omega$ = angular velocity of the rotating magnet in revolutions per second.

Examples A and B show how Equation 1 is used in solving problems.

| EXAMPLE A: ALTERNATOR OUTPUT FREQUENCY | |
|---|---|
| Given: | An alternator has four pole pairs and an angular velocity of 15 revolutions per second. |
| Find: | Frequency of the waveform produced. |
| Solution: | $f = N\omega$<br>$= (4 \text{ pole pairs})(15 \text{ revolutions per second})$<br>$f = 60$ Hz |

| EXAMPLE B: DETERMINATION OF ALTERNATOR ANGULAR VELOCITY | |
|---|---|
| Given: | An alternator has 10 pole pairs and frequency of 60 Hz. |
| Find: | Revolutions per second (rps). |
| Solution: | $f = N\omega$<br>$\omega = \frac{f}{N}$ |

$$\omega = \frac{60 \text{ Hz}}{10 \text{ pole pairs}}$$
$$\omega = 6 \text{ rps}$$

The relationship between frequency, pole pairs, and alternator angular velocity shown in Examples A and B is used in actual alternator applications. Most steam turbines operate efficiently at high angular velocity, allowing single pairs of magnetic poles to be employed in alternators driven by steam turbines. Water-driven alternators rotate at a lower velocity and, therefore, contain a greater number of magnetic pole pairs. Figure 3 shows a rotating magnet (rotor) having several pairs of magnetic poles. Each pole is produced by a magnet.

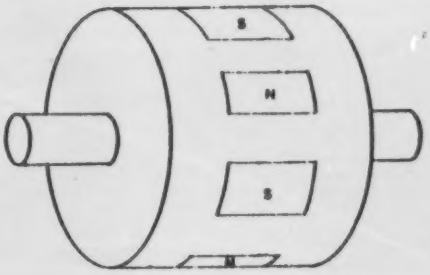



FIG. 3

Permanent magnets can be used in alternators to establish the magnetic lines of force, but this is seldom done in actual practice. Recall from Module 9E1 that the magnitude of voltage produced by a generator can be regulated by varying the strength of the magnetic field that cuts the conductor. An electromagnet must be used in order that strength of the magnetic field can be changed by current adjustment in the electromagnet. When the magnetic coil illustrated in Figure 4 is placed inside an iron shell, the multiple-pole pairs shown in Figure 5 is the result. The

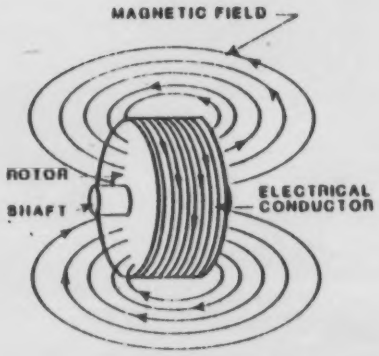



FIG. 4

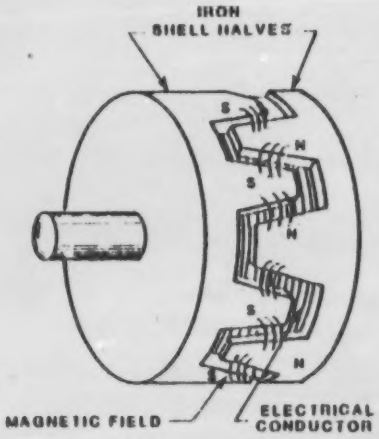



FIG. 5

strength of the many magnetic fields established by the fingers of the iron shell depends upon the amount of current in the inner coil.

At least a small amount of voltage can be generated with a field current of zero. This generation is possible because of the residual magnetism of the armature and may be the case for some automobile alternators. Large industrial alternator applications do not rely upon residual magnetism of the rotor to produce a magnetic field for voltage generation when the alternator is started with no voltage present. Diesel- or oil-driven d.c. generators produce a voltage, called "excitation voltage," to supply the field current for the rotor when the alternator is to be started.

Current to regulate the field strength of the rotating magnet flows through the slip-rings and brushes, as shown in Figure 6. This current, known as the "field current," is much less than the

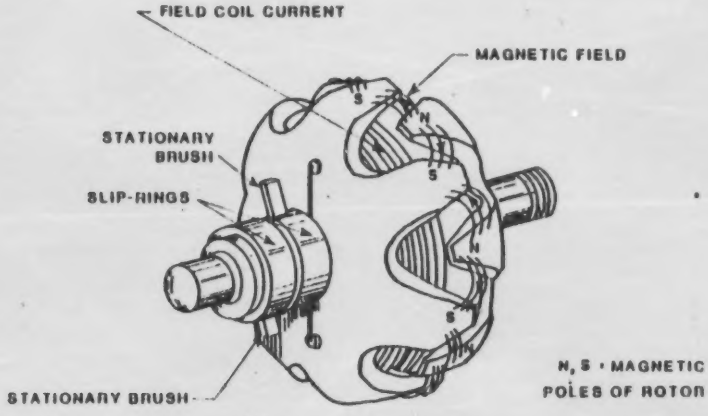



FIG. 6

current in the "stator," which carries the load on the alternator. Thus, the slip-rings and brushes are less likely to fail with this arrangement than if required to carry the load current, as is the case with the stationary-field and rotating armatures of the d.c. generator. The component parts of an automobile alternator are displayed in Figure 7.

Automobile alternators contain as many as seven or more pole pairs. In order for the multiple pole arrangement to function effectively, each pair of poles must have a coil in the stator

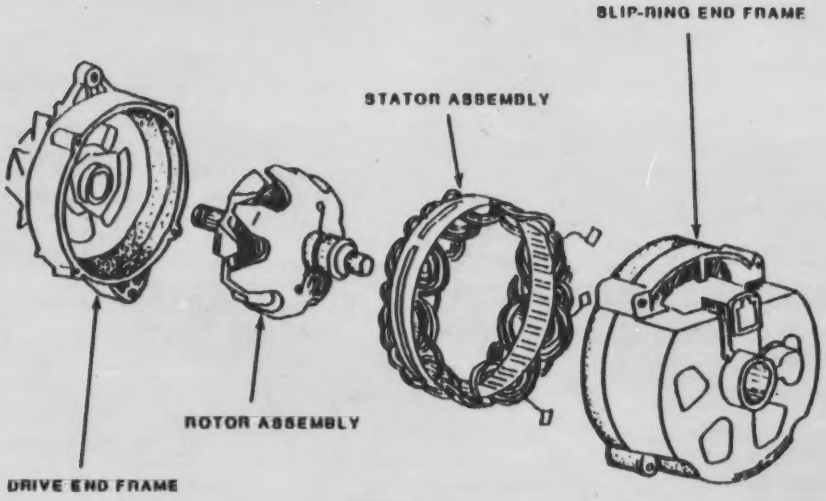



FIG. 7

assembly. All the coils are connected in series to produce an output voltage equal to the product of the number of coils times the voltage produced by a single coil; that is, if an alternator contains seven pole pairs, the voltage output will be seven times as great as with 1 pole pair. Alternators are used on later-model automobiles to generate larger amounts of electrical power than the d.c. generators that were used previously.

In order to increase the electrical power produced by an alternator, coils in the stator are arranged in such a manner that the generation of a waveform is begun every 120° of rotor rotation. The resulting waveform is illustrated in Figure 8. When the value of one waveform decreases, another waveform is generated. This process decreases the net voltage variations and makes rectification easier. Such multiphase generation is utilized for

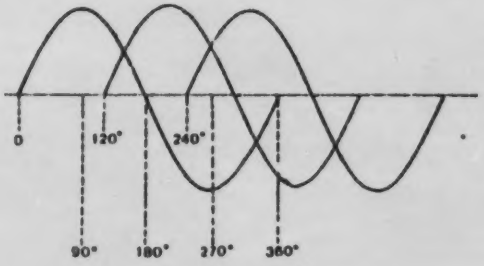



FIG. 8

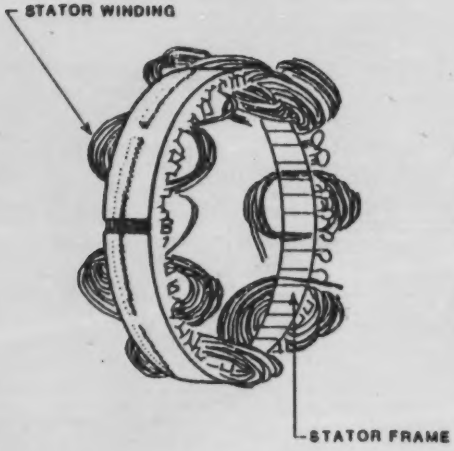



FIG. 9

large electrical devices in industry, to provide more efficient operation.

One set of coils for a seven-pole magnet is displayed in Figure 9. This set of coils produces one of the voltage waves of Figure 8. Two more sets of seven coils are shown in Figure 10, for a total of three sets of seven coils for multiphase generation.

Figure 11 consists of a circuit to rectify the waveform of Figure 8 for d.c. applications. The diodes used for rectification act as electrical check values to allow current to flow in only one direction. Each coil set from the multiphase alternator is connected at points A, B, and C, respectively, of the rectifier circuit. Point D is the common connection of the opposite ends of the three coil sets to the negative output terminal of the alternator. Figure 12 shows the three electrical waves produced before rectification, the result of rectification, and the alternator output voltage as a function of time.

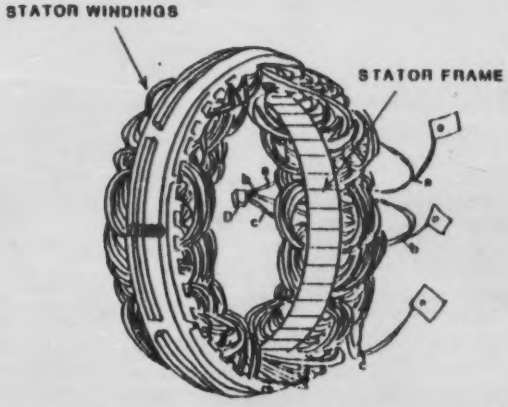



FIG. 10

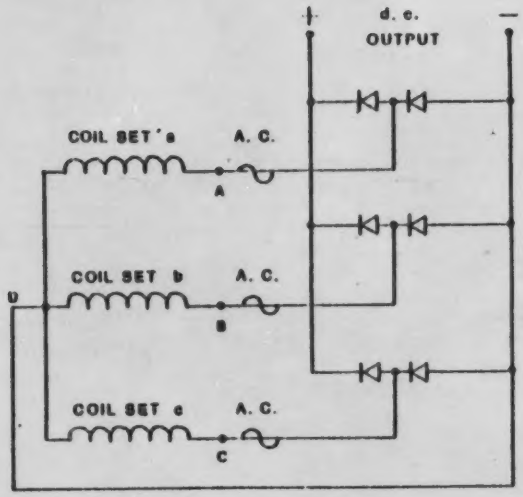

+
d. c.
OUTPUT
—
COIL SET 'a
A. C.
A
COIL SET b
A. C.
B
COIL SET c
A. C.
C

FIG. 11

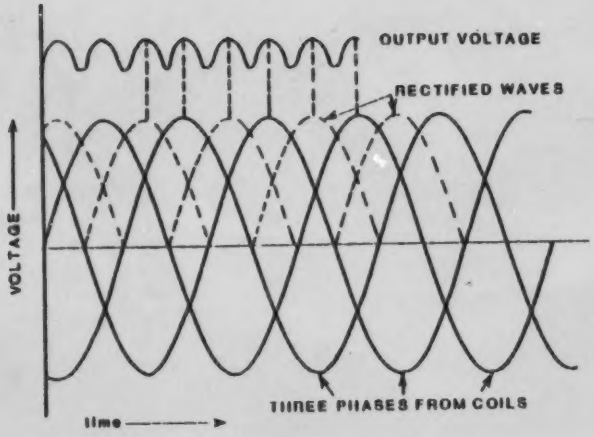

OUTPUT VOLTAGE
RECTIFIED WAVES
VOLTAGE
THREE PHASES FROM COILS
time

FIG. 12

## SUMMARY

In an electric generator, a voltage is produced in a conductor that moves through a magnetic field. In an alternator, the voltage is produced as the magnetic field moves through stationary coils. The magnetic field of the alternator rotor is created by a field current carried to a coil through brushes and slip-rings. The much larger output current is carried by the stationary coils that require no brushes. Thus, alternator brushes can be much smaller than generator brushes, and are subject to less wear. Alternator rotors can be much smaller and lighter in weight than generator rotors, because the lower rotor current allows smaller conductors. For maximum efficiency, alternators often are constructed with several magnetic pole pairs in the rotor and three sets of stator windings for three-phase operation. Alternators produce most of the world's electrical power.

## OUTPUT POWER OF AN ALTERNATOR

### MATERIALS

An alternator (similar to automobile type).
Small variable-speed a.c. or d.c. electric motor to drive alternator.
Variable power supply for motor.
Oscilloscope.
Assorted resistors.
VOM.
3 SPST switches.

### PROCEDURE

1. Connect the motor and alternator as shown in Figure 13.

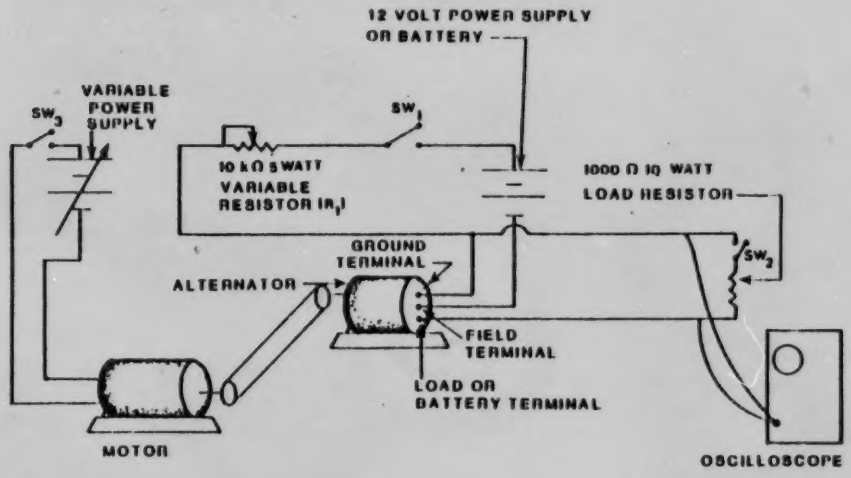



FIG. 13

2. Open switches $SW_1$, $SW_2$, and $SW_3$.

3. Adjust voltage of variable power supply to zero, and close $SW_3$.

4. Slowly increase the motor voltage until alternator output is barely detected on oscilloscope. Observe and note waveform.

5. Increase motor voltage until motor is turning at a moderate speed. Take appropriate readings, and enter in Column 1, Trial 1, of Data Table.

6. Set $R_1$ for its maximum value, close $SW_1$, and slowly increase field current, until an increase in output voltage is detected on the oscilloscope. Measure and record appropriate values in Data Table for Trial 2.

7. Increase field current in three separate increments, and enter appropriate data in Column "A" of Data Table.

8. Open $SW_1$ and $SW_3$. Close $SW_2$. This procedure places a load on the alternator. To study operation of the alternator under load conditions, complete the following steps:

9. Close $SW_3$, and adjust motor current to produce the same alternator output voltage detected in Step 5. Because of the load on the alternator, a field current may have to be established in order to obtain the desired voltage at a moderate rate of motor speed. If this is the case, set $R_1$ for its maximum value, close $SW_1$, and increase the field current for the voltage noted in Step 5.

10. Repeat Step 7, and enter data in Column "B" of Data Table.

11. Observe alternator output waveform on oscilloscope.

12. Increase voltage to motor until a change in motor speed is detected.

13. Observe the waveform.

14. The motor power and generator power can be calculated from data entered into Data Table. (Power = VI.)

15. To calculate overall efficiency, divide power out by power in, and multiply by 100:

$$\eta = \frac{P_{out}}{P_{in}} (100)$$

This equation gives the efficiency of the motor-alternator pair in converting electrical energy to mechanical energy and back to electrical energy.

16. Explain two factors that affect the output of the alternator and the effects of each.

| DATA TABLE | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Trial | Motor Voltage | | Motor Current | | Motor Power | | Field Current | | Alternator Output | | | | Overall Efficiency |
| | | | | | | | | | Voltage (V) | | Current (A) | Power (W) | |
| | A | B | A | B | A | B | A | B | A | B | B | B | B |
| 1 | | | | | | | | | | | | | |
| 2 | | | | | | | | | | | | | |
| 3 | | | | | | | | | | | | | |
| 4 | | | | | | | | | | | | | |
| 5 | | | | | | | | | | | | | |
| A - No load condition<br>B - Load condition | | | | | | | | | | | | | |

## SELF CHECK

1. Draw and label diagrams showing a magnet rotating inside a coil of wire and showing the waveform generated in the wire.

2. Draw and label the rotor of an automobile alternator, showing the field coil, the brushes, and the magnetic poles.

3. A three-phase alternator rotates at 360 r/min (rpm) and produces a 60-Hz output. How many pole pairs does its rotor contain? How many coils does its stator contain?

4. Why is most electricity produced by alternators instead of generators?

5. A three-phase alternator has a total of 27 coils in its stator and rotates at 420 r/min (rpm). What frequency is produced?

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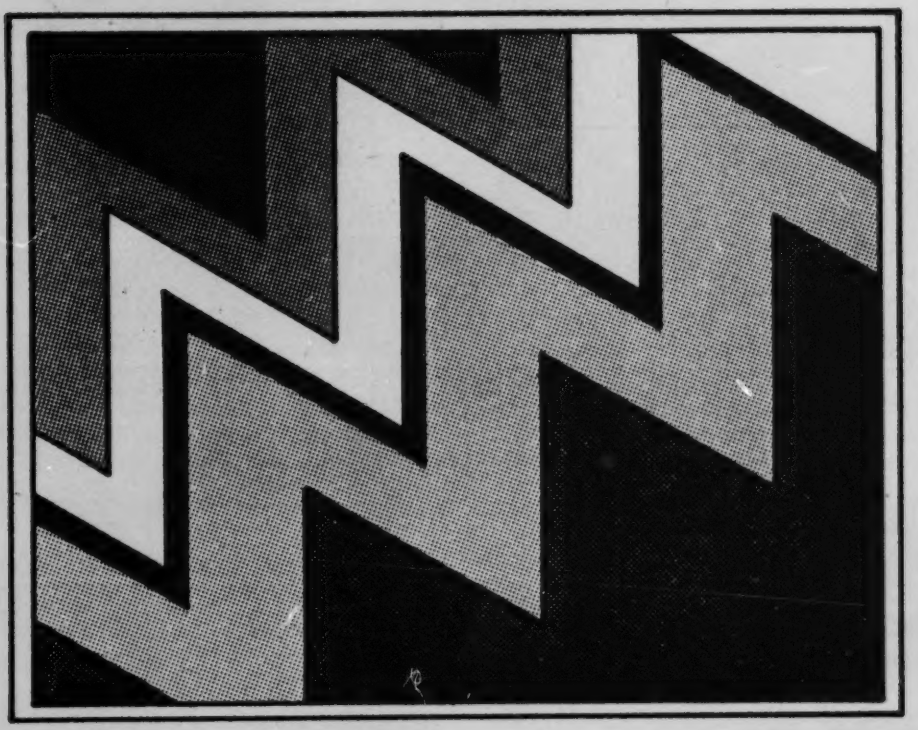
UNIFIED TECHNICAL CONCEPTS

MODULE 9 E 3

ELECTRIC MOTORS



ELECTRICAL APPLICATION OF ENERGY CONVERTORS

Technical Education Research Center - Southwest

TERC - SW

## INTRODUCTION

One of the most essential and versatile energy converters utilized by modern technology converts electrical energy into mechanical energy. The device that accomplishes this conversion is called an "electric motor." The advantages offered by electric motors are numerous — they are mechanically simple, quite, clean to operate, and relatively efficient.

This module introduces the principles governing the operation of direct-current (d.c.) electric motors. In the laboratory, the student will build and operate a permanent-magnet motor and a series motor.

## PREREQUISITES

Student should have completed Concept Module 9-0, "Energy Converters," and Application Module 1E4, "Magentic Forces and Fields."

## OBJECTIVES

Upon completion of this module, the student should be able to:

- Use the left-hand motor rule to determine the direction of the force on a current-carrying conductor in a magnetic field.
- Given a diagram of a loop of wire carrying a current in a magnetic field, determine the direction of loop rotation.
- Sketch a permanent-magnet d.c. motor. Label and explain the function of the principal parts.
- List the three factors that determine the magnitude of the torque produced by an electric motor.
- State the difference between permanent-magnet, series, and shunt d.c. electric motors.

- Given the appropriate equipment, build and operate a simple permanent magnet motor, and show how it can be converted into a series motor.

## DISCUSSION

The rotation of an electric motor is caused by the forces that act upon current-carrying wires in the motor because of the presence of a magnetic field. Operation of an electric motor is made possible by the nature and direction of these forces.

The direction of the force acting on a current-carrying wire in the presence of a magnetic field is determined by the Left-hand Motor Rule. Figure 1 shows how the motor rule is applied. The thumb, forefinger, and middle finger of the left hand are held at right angles to each other. If the forefinger is pointed in the direction of the magnetic field B, and the thumb is pointed in the direction of electron flow, then the middle finger will point in the direction of the magnetic force acting on the wire. Hence, the force on the wire in Figure 2a is straight up. If the direction of electron flow is reversed as in Figure 2b, the force on the wire is in the opposite direction. If the direction of electron flow is parallel to the magnetic field, there is no magnetic force acting on the wire (Figure 2c).

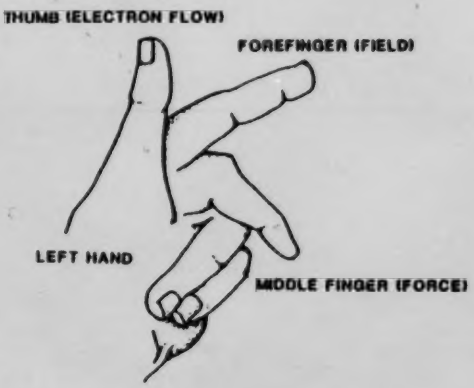



FIG. 1

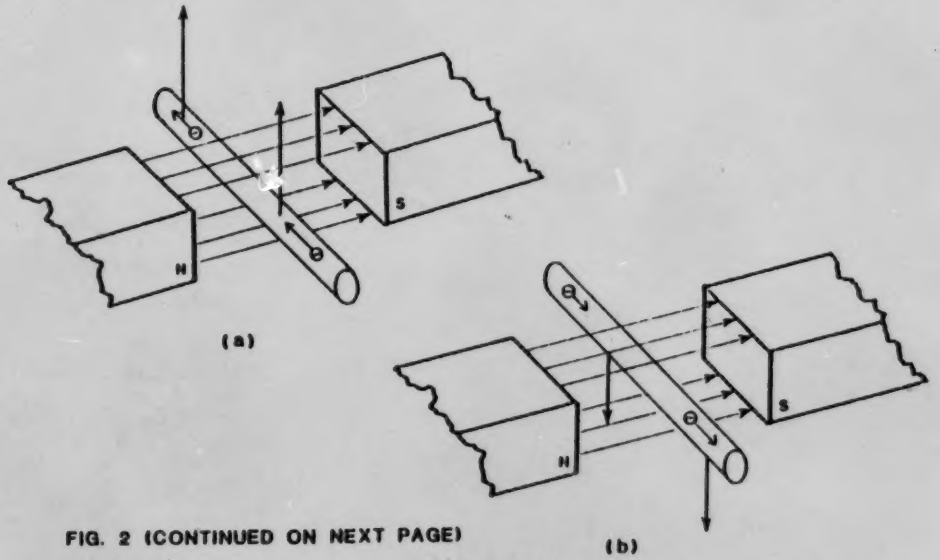
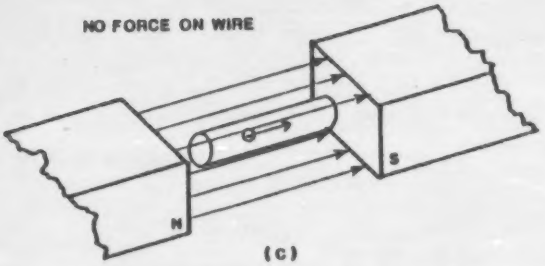
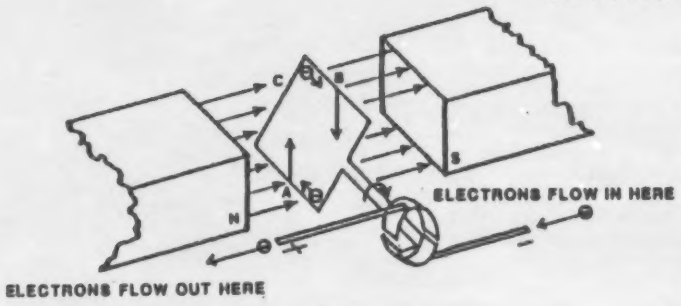



FIG. 2 (CONTINUED ON NEXT PAGE)

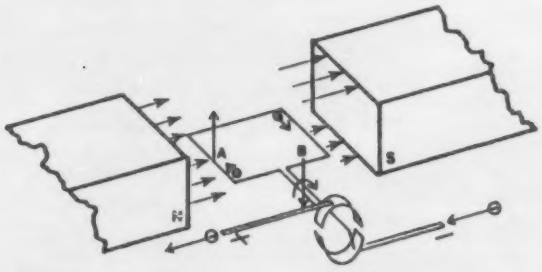



(c)

FIG 2 (CONTINUED FROM PREVIOUS PAGE)




(a)




(b)

FIG. 3 (CONTINUED ON NEXT PAGE)

Figure 3a shows how a simple electric motor is constructed from a square loop of wire, called the "armature," and from a "split-ring commutator." Because the magnetic field is provided by two permanent magnets, this configuration is called a "permanent-magnet motor."

In Figure 3a, electrons flow into the loop through the upper contact, or brush, and out through the lower brush. Magnetic force is directed upward on Segment A and downward on Segment B. These oppositely-directed forces exert a net torque on the armature, causing it to rotate in a clockwise direction. This torque on the armature is plotted as Point "a" on the graph of Figure 4. Magnetic forces also act on wire Segment C; these forces, however, are always parallel to the axis of rotation and, therefore, never contri-

bute to the torque acting on the armature. For this reason, the forces on Segment C are unimportant and will be disregarded.

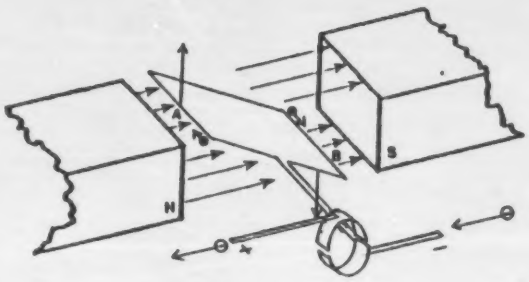
A short time later the armature has rotated to the position shown in Figure 3b. Since the forces acting on A and B depend only upon the current and upon the magnetic field strength, they have not changed. The torque acting on the armature has increased, however, because of the increase in the lever arm associated with each force. This configuration produces the maximum torque on the armature (Point "b" on Figure 4).

In Figure 3c, Segments A and B are still being pulled upward and downward, respectively. The torque is smaller because of a reduced lever arm (Point "c" on Figure 4), and the armature continues to rotate clockwise.

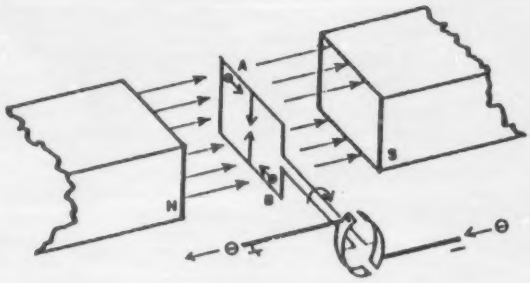
Just as the loop achieves the vertical orientation shown in Figure 3d, each brush slips to the opposite segment of the commutator ring, causing the direction of electron flow to be reversed. The forces on Segments A and B change direction, pulling A downward and pushing B upward. No torque acts on the loop, however, since the lever arm for each force is zero. (See Point "d" on Figure 4.)

Although no torque acts on the armature in Figure 3d, the momentum it already has built up allows it to coast into the position in Figure 3e, and the process repeats itself.

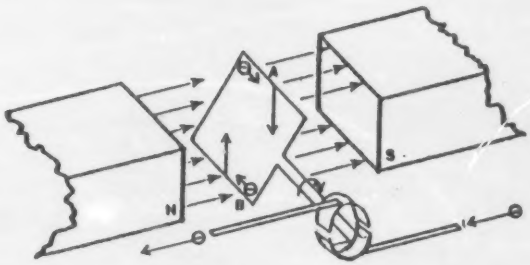
For ordinary magnetic fields and currents, the torque acting on a single loop of wire generally




(c)




(d)




(e)

FIG. 3 (CONTINUED FROM PREVIOUS PAGE)

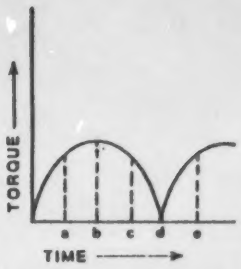



FIG. 4

is too small for practical application. Torque can be made larger by use of an armature that consists of many loops of wire, as shown in Figure 5. As current flows through the armature, a torque acts on each single loop. Each of these individual torques add to produce the total torque on the armature. Figure 6 shows the net torque acting on the motor of Figure 5 as a function of time. The maximum torque produced by the motor is determined by three factors:

- The number of loops in the armature.
- The strength of the magnetic field.
- The current flowing through the armature.

When any of these factors is increased, the torque increases.

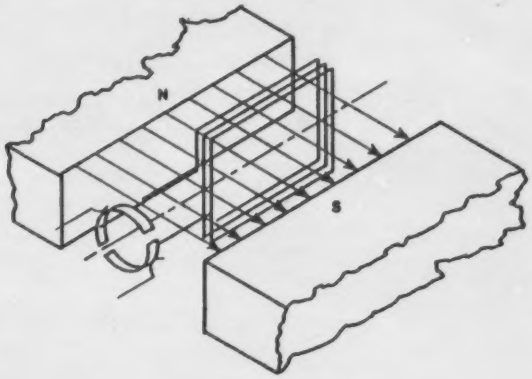



FIG. 5

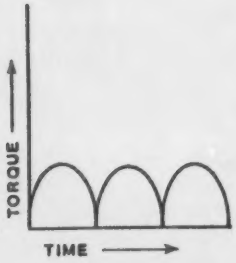



FIG. 6

Usually, permanent magnets can be used to provide the magnetic field in only very small motors. More powerful electric motors require a larger magnetic field than normally is available from permanent magnets. This problem is solved by the replacement of permanent magnets with electromagnets called "field coils."

Figure 7a shows a "series motor," so named because the field coils are connected in series with the armature. The same current flows through the field coils and the armature. Figure 7b shows a "shunt motor," in which the field coils are connected in parallel with the armature. Current through the field coils then is completely indepen-

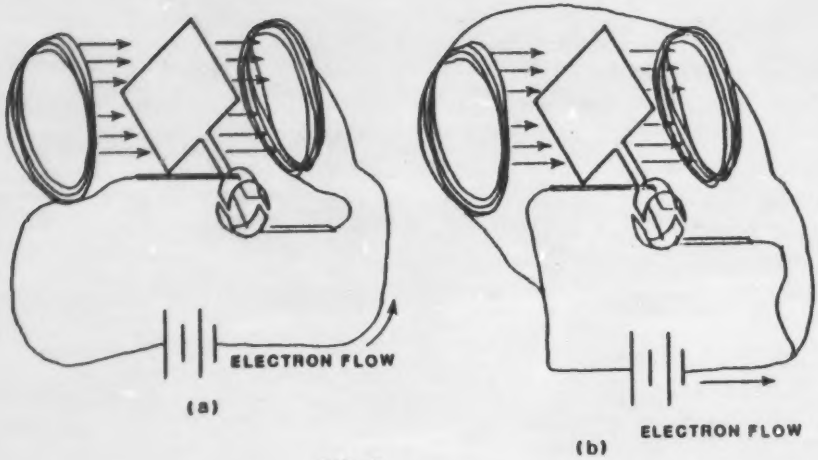



FIG. 7

dent of the armature current.

One problem with the motors discussed so far is that the torque acting on the armature varies greatly during a single revolution. This variation causes excessive wear on the bearings in the motor, and generally causes it to "run rough." Use of a modified armature, called a "multipole armature," causes the torque acting on it to be more nearly constant and to result in smoother operation.

A section view of the multipole armature is shown in Figure 8. This armature consists of many different coils of wire wrapped at equal intervals around the armature. The ends of each coil are connected to opposing segments of the commutator. The brushes are oriented in such a manner that they contact the commutator segments of each coil in the maximum torque orientation. The resulting torque is shown in Figure 9 as a function of time.

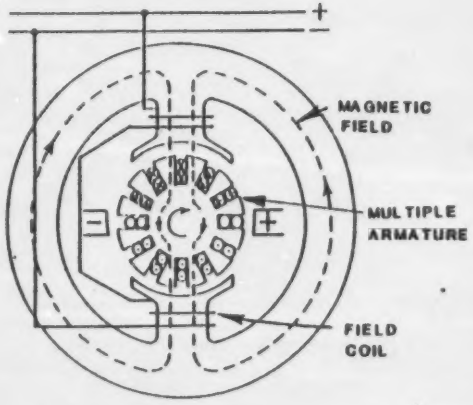



FIG. 8

When an electric motor is rotating, the electrons in its armature windings actually undergo two distinctly different motions through the magnetic field. One motion, that of

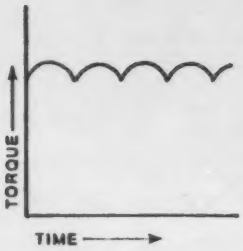



FIG. 9

the current flowing along the wire, already has been discussed in some detail in this module. This motion causes the magnetic forces that produce the torque on the motor; however, the electrons are carried around in a circular path by the spinning armature exactly as they would be in an electric generator. When the Left-hand Generator Rule is applied, an additional force is shown to be acting on the electrons. This force pushes against the flow of electrons in the armature, resulting in a voltage being produced across the armature. This voltage is opposite in polarity to the input voltage of the motor, and is called the "back emf." The back emf serves to decrease the armature current when the motor is spinning.

## SUMMARY

The electric motor converts electrical energy into mechanical rotational energy. Its operation is made possible by the magnetic field inside the motor and by the forces exerted by the field upon conductors passing through it. The maximum torque developed by a particular motor depends upon (1) the number of loops in the armature, upon (2) the strength of the magnetic field, and upon (3) the current flowing through the armature.

## THE PERMANENT-MAGNET MOTOR

### MATERIALS

Variable d.c. power supply, 0-6V, 5A, with meter to indicate output voltage.
Horseshoe magnet with north and south poles labeled.
Cork.
Razor blade.
Needle-nose pliers.
Eight straight pins.
Two thumb tacks.
Soft wooden base.
Twenty feet of #30 insulated copper wire.
Two strips of tin or copper foil 1/4" x 2".
Wire connectors.

### PROCEDURE

1. Cut a groove in cork with razor blade, as shown in Figure 10a. Stick a pin in each end of cork to act as an axle.

2. Wrap wire in groove around cork to form armature of motor. Trim wire in order that coil starts and terminates at same end of cork. Leave about one inch of each end of the wire free. Strip ends by scraping with razor blade.

3. Make commutator by sticking two more pins in cork, as shown in Figure 10b. Wrap each end of armature coil around a different pin, as shown.

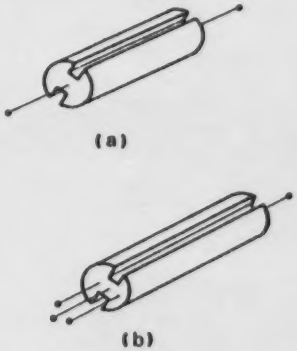



FIG 10

4. Build mounting stand for motor by sticking remaining pins into wooden base, as in Figure 11a. Place armature in mounting stand; be sure that it is level and spins freely.

5. Construct brushes from strips of tin foil held in place by thumb tacks. Adjust brushes in such a manner that each makes simultaneous contact with commutator when armature is turned by hand. Contact between brushes and commutator should be light, in order that armature rotation will not be

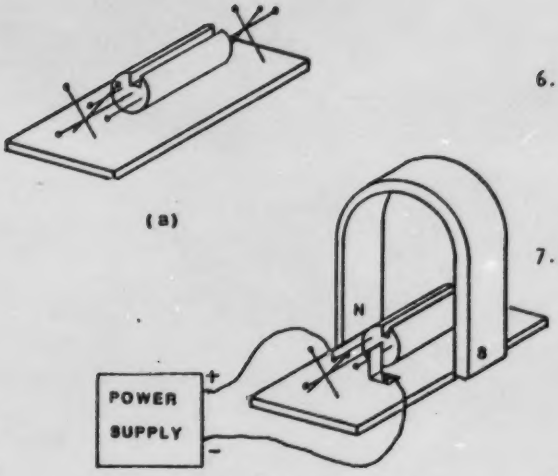



FIG 11

impeded.

6. Run a separate wire connector from each pole of power supply to one of the brushes, as shown in Figure 11b. Place horseshoe magnet over armature, as shown. The motor is now complete.

7. Label Figure 11b with the following information:
   - Direction of magnetic field.
   - Direction of electron flow through the armature.
   - Forces acting on the horizontal segments of wire in the armature.
   - Direction of armature rotation.

8. Turn on power supply, and set it to about 1.5 V. Spin motor gently to get it started. Record direction of rotation in Data Table 1.

9. Reverse poles of magnet so that direction of magnetic field is opposite its original direction. (Turn off power supply before making any changes.) Record direction in which the armature spins. Make a sketch similar to Figure 11b to justify this observation.

10. Return the magnet to its original orientation, and reverse leads on power supply. Record direction in which motor now spins, and justify with a sketch.

11. Record and justify with a sketch the effect of reversing both the magnet and power supply leads from their original positions.

## THE SERIES MOTOR

### MATERIALS

Pin and cork motor built in previous laboratory exercise.
Variable d.c. power supply, 0-6V, 5A, with meter to indicate output voltage.
Two nails 4" in length.
Two blocks of wood.

Seven feet of #20 insulated wire.

## PROCEDURE

1. Drive one nail approximately one inch into each block of wood. When blocks are laid on their sides, each nail should be parallel to table top, at approximately equal heights above it. Heads of nails should be at about the same height as axle of motor.

2. Strip about 1/2 inch of insulation from each end of #20 wire. Refer to Figure 12. Starting about 3 inches from one end, wrap about three feet of wire around one nail. Starting about three inches from opposite end, neatly wrap three feet of wire around other nail. Be sure that wire is wound in same direction around each nail. When you are finished, wrapped nails should look like those in Figure 2a. These are the field coils.

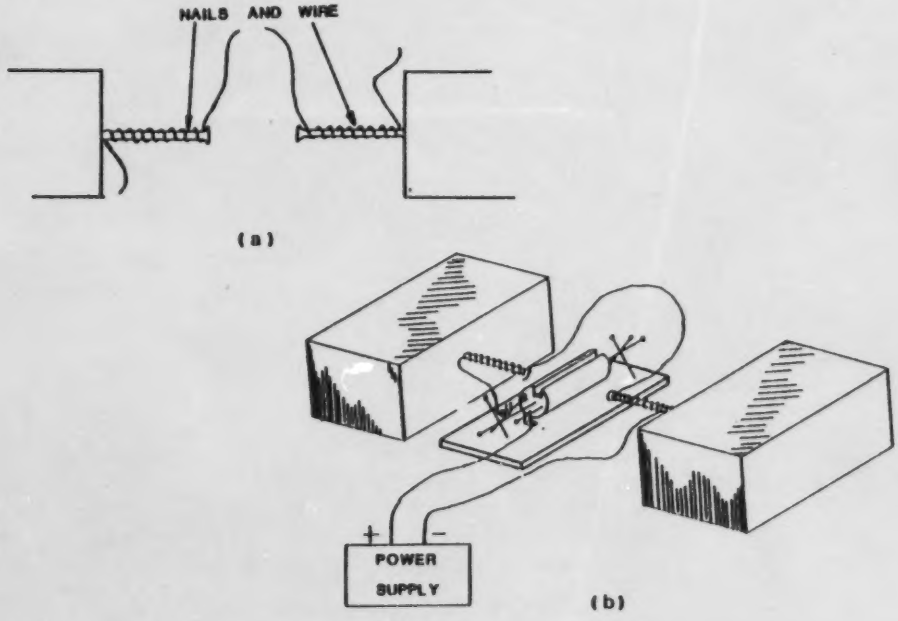



FIG. 12

3. Connect field coils, motor, and power supply, as shown in Figure 12b. Wires may be attached to each other by twisting them together. Place field coils opposite each other, with armature directly between them. Heads of nails should be as close to one another as possible without interfering with spinning armature.

4. Turn on power supply, and adjust it to approximately 3V. Start motor spinning, and record direction of spin in Data Table 2.

5. Determine and record effect of the following changes on direction of rotation of armature:

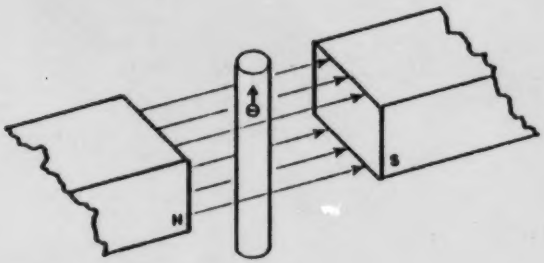
   - Changing each field coil to the opposite side of armature.
   - Reversing power supply leads.
   - Reversing both field coil positions and power supply leads.

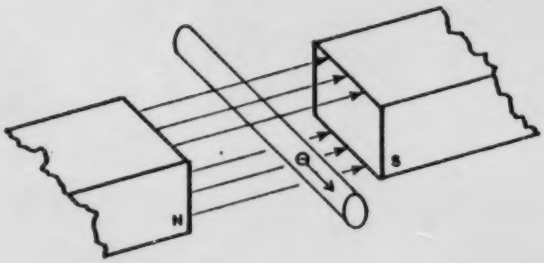
6. What are the basic difference between the permanent-magnet, series, and shunt motors?

| DATA TABLE 1 | |
|---|---|
| Original spin direction: | _____ |
| Spin direction with only magnet reversed: | _____ |
| Spin direction with only power supply leads reversed: | _____ |
| Spin direction with both magnet and leads reversed: | _____ |

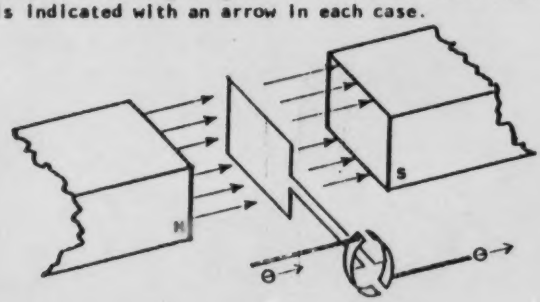
| DATA TABLE 2 | |
|---|---|
| Original spin direction: | _____ |
| Spin direction with field coils reversed: | _____ |
| Spin direction with power supply leads reversed: | _____ |
| Spin direction with field coils and power supply leads reversed: | _____ |

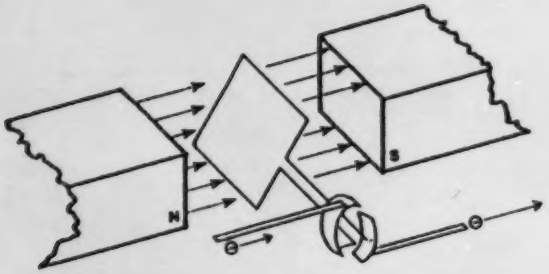
1. Determine the direction of the force on the current-carrying wires in the following diagrams. The direction of electron flow is indicated in each case.

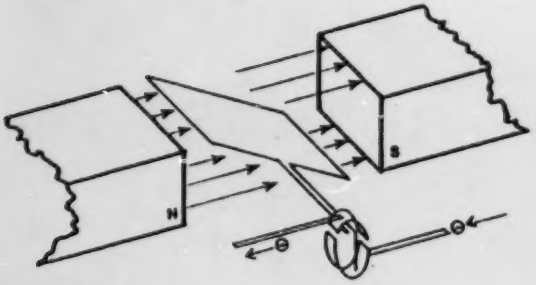



2. Indicate the direction of rotation of the current-carrying loops in the following diagrams. The direction of electron flow is indicated with an arrow in each case.






3. Sketch a permanent-magnet electric motor. Label the magnets, armature, commutator, and brushes; and explain the function of each.

4. List the three factors that determine the maximum torque produced by a motor.

5. State the difference between the permanent-magnet, series, and shunt motors.

# REFERENCES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(See pp. 361-364 for another easy-to-build d.c. motor.)

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(See pp. 182, 183 for more easy-to-build motors.)

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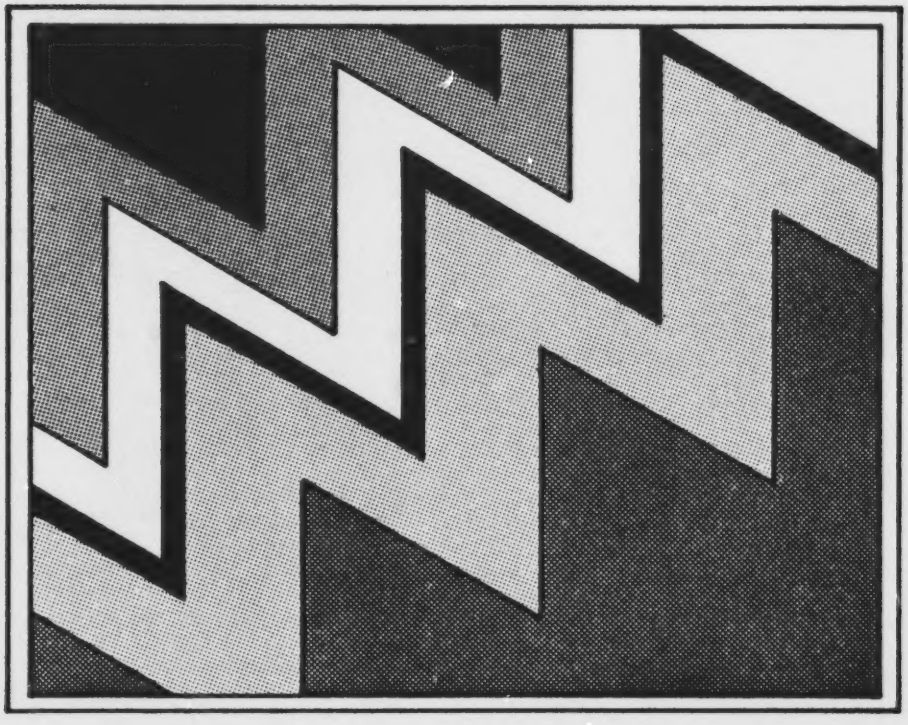
UNIFIED TECHNICAL CONCEPTS

MODULE 9 E 4

SOLENOIDS AND RELAYS



ELECTRICAL APPLICATION OF ENERGY CONVERTORS

Technical Education Research Center - Southwest

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## INTRODUCTION

Electromechanical devices are energy converters that use both electrical and mechanical energy. In a solenoid, an electrical current flows through a coil of wire to produce a magnetic field. This magnetic field causes an iron plunger to be magnetized and drawn into the center of the coil, converting electrical energy into mechanical energy. The resulting mechanical motion can be used to operate switches, valves or other mechanical devices. When a solenoid is used to operate a switch, the entire device is called a relay. This module discusses the operation and applications of the solenoid and the relay. In the laboratory, the student will identify relay terminals and will operate starter and control circuits.

## PREREQUISITES

Student should have completed Concept Module 9-0, "Energy Converters," and Application Module 1E4, "Magnetic Forces and Fields."

## OBJECTIVES

Upon completion of this module, the student should be able to:

- List and explain the operation of the three components of a solenoid.
- Describe how the plunger of a solenoid is drawn into the coil form by a magnetic field.
- State the purpose of a relay.
- Draw and label a diagram showing a single-pole, single-throw relay in a control circuit.
- Draw and label diagrams showing the contacts of the following relays:

  Single-pole single-throw.
  Single-pole double-throw.

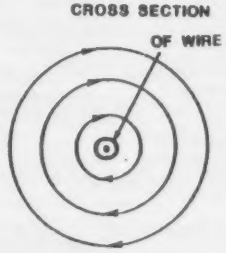
Double-pole single-throw.
Double-pole double-throw.

- List three electrical devices that employ relays.
- Given the appropriate equipment, identify relay terminals and operate an automobile starter circuit and an electric motor control circuit.

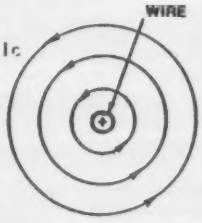
## SOLENOIDS

The Danish scientist Hans Christian Oersted discovered in 1820 that an electric current flowing in a wire causes a magnetic field around the wire. The production and control of a magnetic field by an electric current is the basis of the solenoid.

Figure 1 shows the magnetic field produced by a long, straight wire carrying a current. In Figure 1a, electron current flows toward the reader out of the plane of the page (indicated by a dot) and sets up the resulting circular magnetic field, pointing in a clockwise direction. In Figure 1b, the current direction is reversed to flow into the page (indicated by a cross), and the direction of the magnetic field also is reversed.




(a) CURRENT OUT OF PAGE




(b) CURRENT INTO PAGE

FIG. 1

In Figure 2, two current-carrying conductors are placed close together. If both currents flow in the same direction (into the page in this case), the magnetic fields combine, as shown, to produce a stronger field. Additional conductors with the same current direction would further increase the strength of the magnetic field.

If the wire is coiled as shown in Figure 3, a stronger magnetic field within the coil results. The arrows in the figure show the direction of the magnetic field around the wire at all points. The fields in Figure 3 always point downward inside the coil and upward outside. These small fields produce the total magnetic field of the coil shown by dotted field lines. This magnetic field produces mechanical motion in a solenoid.

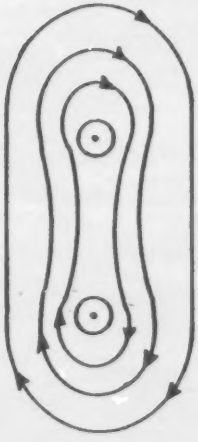


FIG. 2

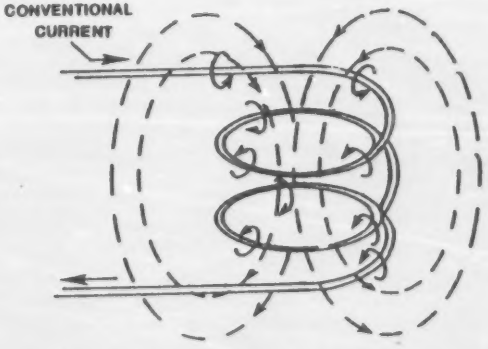



FIG. 3

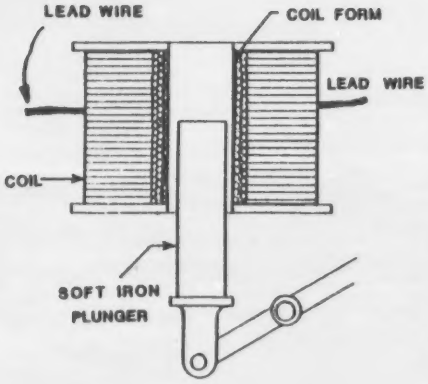



FIG. 4

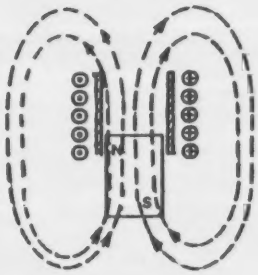



FIG. 5

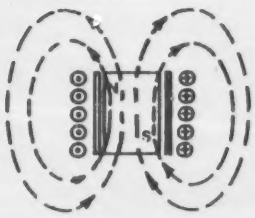



FIG. 6

Figure 4 shows the three components of a solenoid. A coil of wire is wrapped around a hollow coil form made of a non-magnetic material. The plunger is a cylinder of ferro-magnetic material (usually iron) that slides easily inside the coil form. The plunger is situated partially inside the coil form when the coil is not energized.

When a current begins to flow in the coil (Figure 5), the magnetic field around the coil is established. The coil behaves as a magnet with N pole at the top and S pole at the bottom. The field is distorted by the presence of the iron plunger. It passes through the iron and causes it to be magnetized as shown. The north pole of the plunger is pulled upward by the magnetic field of the solenoid, and the south pole is pushed downward. Because the north pole is in a stronger part of the field than the south pole, the upward force is greater than the downward force; and the plunger moves upward until it is centered in the coil form (Figure 6). Upward motion of the plunger can be used to operate valves, switches or other mechanical devices. When the current is interrupted, the magnetic field disappears and the plunger is returned to its original position by gravity or by a spring. Solenoids are used in a variety of applications including liquid and gas flow valves, door bells and electric locks for automobile doors.

## RELAYS

The most common application of the solenoid is in a device called a relay (Figure 7). A solenoid is used in a relay to operate a switch, allowing a small voltage and current to be used to control larger voltages or currents. In Figure 7 the control switch is open and no current flows in the coil of the relay. The plunger is held down by a spring, and the relay switch is open, which prevents current flow in the controlled circuit. When the control switch is closed (Figure 8), a current flows in the relay coil, pulling the plunger into the coil form. This stretches the spring and closes the relay switch, completing the controlled circuit. When the control switch is opened again, the magnetic field disappears; and the spring pulls the plunger downward to reopen the relay switch.

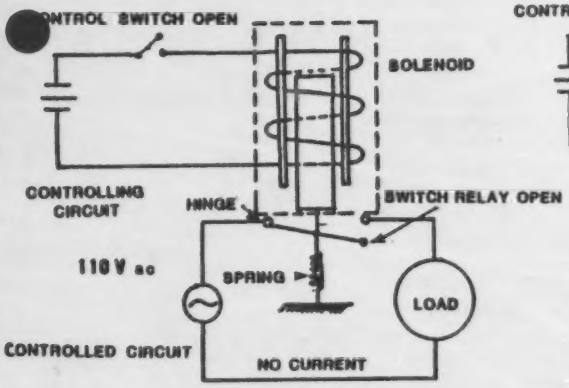



FIG. 7

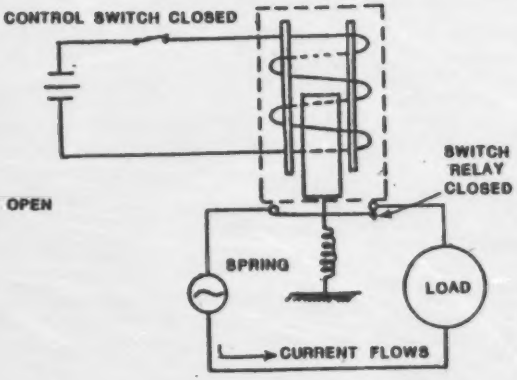
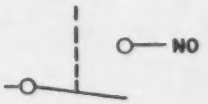


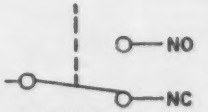

FIG. 8

The relay shown in Figure 7 is called a single-pole, single-throw (SPST) relay, which means that it contains a single switch that completes one circuit when the control switch is closed (thrown). In many cases, control of more than one circuit with one relay is desirable. This control is accomplished by adding more switches or by allowing a relay to break one circuit when it completes another. Switch contacts that are closed when the relay coil is not energized are called normally-closed (NC) contacts. Those that are open when the coil is not energized are called normally-open (NO) contacts. Figure 9 shows the switch contact arrangements for four common types of relays.




SINGLE POLE
SINGLE THROW-SPST

(a)



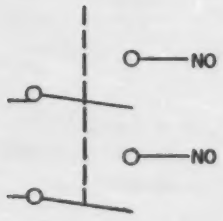

SINGLE POLE
DOUBLE THROW-SPDT

(b)

Relays are available in a wide variety of sizes and designs. Some contain many more switches than shown by the examples in Figure 9 for controlling more circuits. Some are designed for d.c. coil current and others for a.c. coil current. The following specifications often are given on a relay, and are important in selecting the proper relay for a specific job:

- Coil voltage.
- Coil current.
- Number and type of switches.
- Switch current.
- Switch voltage.

Relays are found in most electrical systems in which large currents must be controlled. The following are three



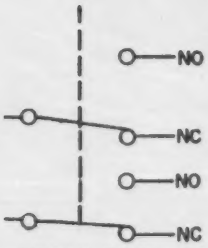

DOUBLE POLE
SINGLE THROW-DPST

(c)

common examples:

- In an automobile, the starter switch operates a relay that controls the starter motor.
- In an electric hot water heater, a temperature sensing device controls a relay that controls the current to the heating elements.
- In an air conditioner, the thermostat operates a relay that controls the current to the compressor and fan motors.

## SUMMARY




DOUBLE POLE
DOUBLE THROW-DPDT

(d)

FIG. 9

The solenoid coverts electrical energy into mechanical energy. It consists of a cylinder-shaped coil of wire through which current is passed and of an iron core (plunger) which is moved by the electromagnetic field produced by the coil. The relay contains a solenoid attached to a switch. Solenoids and realys are used widely in fluid flow control and in a variety of switching operations.

## IDENTIFYING RELAY TERMINALS

### MATERIALS

12 V d.c. relay SPDT.
VOM.

### PROCEDURES

1. Examine relay, and determine which terminals are connected to movable part of relay switch, which are connected to fixed switch contacts and which are connected to relay coil.

2. Set VOM to ohms x 1 scale, and measure resistance of relay coil. Coil resistance varies with relay design but should be between 15 Ω and 200 Ω.

3. Attach one VOM lead wire to terminal connected to movable part of relay switch. Connect other VOM lead to one of terminals connected to a fixed switch contact, and note resistance measured.

4. Repeat with other terminal.

5. From the data determined, identify terminals connected to fixed switch contacts as normally open (infinite resistance reading) or normally closed (zero resistance reading).

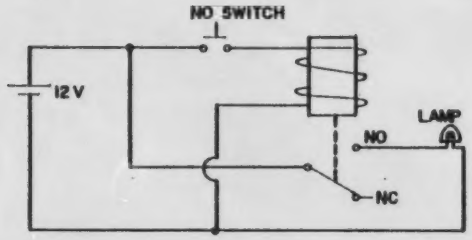
## AUTOMOBILE STARTER CIRCUIT

### MATERIALS

12 V d.c. relay SPDT.
12 V d.c. power supply or 12 V battery.
12 V lamp (to simulate starter motor).
Normally-open push-button switch.
Connecting wires.

**PROCEDURES**

1. Connect circuit as shown in Figure 10.




2. Alternately press and release push button switch while observing relay and lamp operation.

3. Describe circuit operation, and explain why the relay closes.

FIG. 10

## ELECTRIC MOTOR CONTROL CIRCUIT

**MATERIALS**

12 V d.c. relay SPDT.
12 V d.c. power supply or 12 V battery.
Two 12 V lamps.
Normally-open push-button switch.
Normally-closed push-button switch.
Connecting wire.
SPST toggle switch.

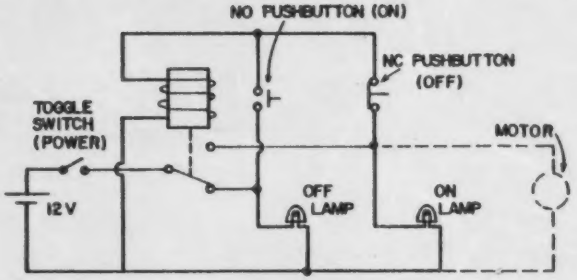
**PROCEDURES**

1. Connect circuit as shown in Figure 11.
2. Turn on power toggle switch.
3. Press and release "on" push-button switch.
4. Press and release "off" push-button switch.

5. Observe circuit operation.

6. If this circuit were attached to a motor as shown in Figure 11, would the motor operate when step 2 was completed, or when step 3 or 4 was completed? Explain.

FIG. 11



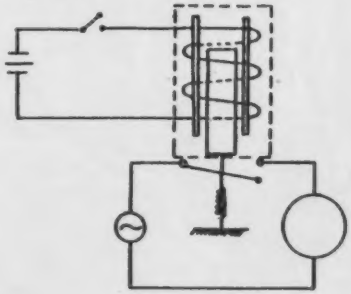

## SELF CHECK

1. List the three components of a solenoid.

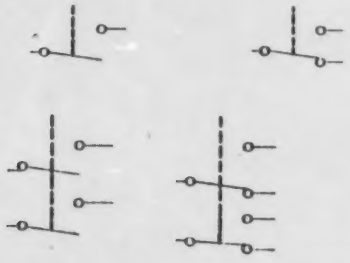
2. Explain how the plunger of a solenoid is drawn into the coil form by the magnetic field.

3. What is the purpose of a relay in an electrical circuit?

4. Label the diagram at the right.



5. Identify each of the relay contact configurations shown below.



6. Name three devices using relays.

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Sears, F.W. and Zemansky, M.W. Modern College Physics, Part II: Fields, Waves, and Particles. Reading, MA: Addison-Wesley Publishing Company, 1965.

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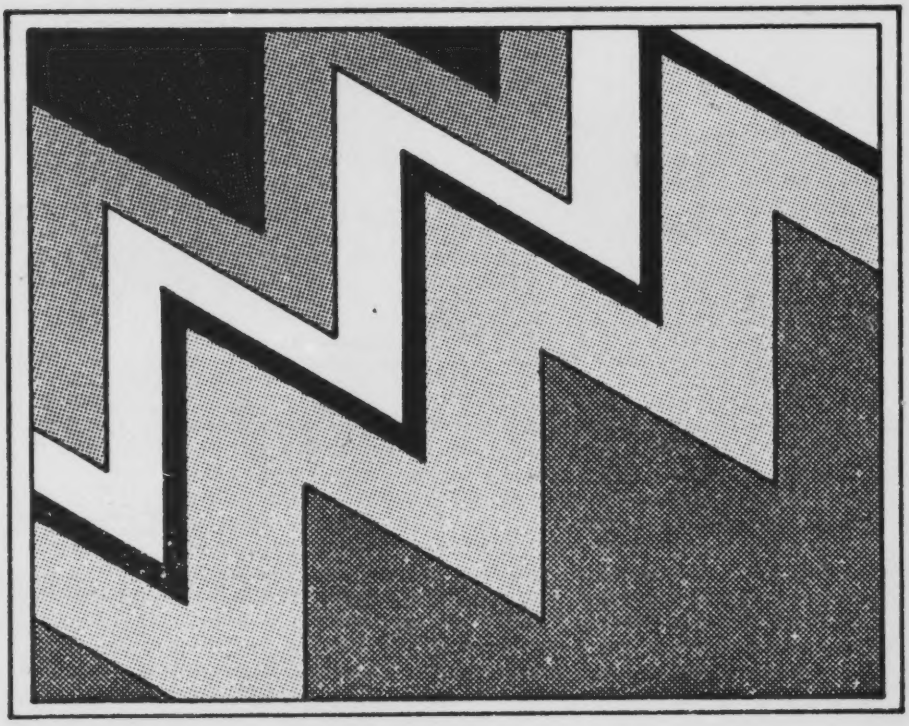
UNIFIED TECHNICAL CONCEPTS

MODULE 9 E 5

PHOTOVOLTAIC MATERIALS



ELECTRICAL APPLICATION OF ENERGY CONVERTORS

Technical Education Research Center – Southwest

TERC – SW

## INTRODUCTION

Photovoltaic materials are semiconductors; specifically, they are junctions between a P-type semiconductor and an N-type semiconductor. When light -- for example, sunlight -- strikes such materials, electrical current is generated. Thus, photovoltaic materials can be used as detectors of light and also as energy converters that convert light directly into electricity.

This module examines the operation and construction of photovoltaic materials. In the laboratory, the student will use a photovoltaic device to measure efficiency of conversion of light energy into electrical energy.

## PREREQUISITES

Student should have completed Concept Module 9-0, "Energy Converters."

## OBJECTIVES

Upon completion of this module, the student should be able to:

- Describe the operation of photovoltaic devices, including energy bands in semiconductors, P-N junctions, generation of free electrical carriers by absorption of light energy near the junction leading to electrical current flow; name at least one useful photovoltaic semiconductor material.
- Describe at least two applications of photovoltaic materials.
- Given the appropriate equipment, use a photovoltaic device to measure the efficiency of conversion of light energy into electrical energy.

An excellent example of an energy converter is the photovoltaic transducer. When energy in the form of light is incident on a photovoltaic material, it is converted directly into electrical energy. Because of this, the photovoltaic transducer has great utility for quantitative measurement of light energy and also for direct generation of electrical energy from light energy such as sunlight.

To understand operation of photovoltaic transducer, we must refer to some of the concepts related to semiconductors, as described in Module 6E5. Most materials used in photovoltaic transducers are semiconductors; therefore, some of the concepts related to semiconductors must be reviewed.

## HOW SEMICONDUCTORS WORK

### N-TYPE JUNCTIONS

As a brief review, remember that a semiconductor is a material with values of electrical conductivity intermediate between those of good metallic conductors, such as copper, and electrical insulators, such as rubber. Examples of semiconductors include materials such as silicon and germanium. The "energy band structure" of semiconductors is important. Current can be carried through a semiconductor by the motion of electrons; however, free electrons in a semiconductor are few in number compared to those in a metal, so that electrical conductivity is much lower. In addition, in a metal the free electrons have a continuous range of energy levels available to them. In a semiconductor, on the other hand, there are bands of allowed energy, separated by a band gap, a range of energies not available to the electrons (Figure 1). Free electrons in the conduction band are free to move under action of an electric field and contribute to electrical conductivity. If the dominant contribution to electrical conduction is free electrons, the material is termed an N-type semiconductor.

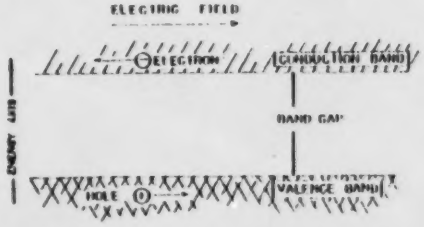



FIG. 1

## P-TYPE JUNCTIONS

Another contribution to electrical conduction can be through missing electrons in the valence band. As electrons from neighboring sites move to fill the vacancy, the position of the missing electron may move. The movable vacancy appears similar to motion of positive charge through the material. The movable vacancy is called a "hole," and it acts like a positive charge carrier. Materials in which the dominant contribution to electrical conduction is the motion of the holes are termed "P-type" semiconductors. Semiconductors can be made P-type or N-type when doped in manufacture with small amounts of appropriate impurity elements.

## P-N TYPE JUNCTIONS

A P-N junction is a region in which there is an interface between P-type and N-type material, of very small dimensions, typically of the order of a few micrometers. Such a junction is called a "P-N junction," which is the important junction for photovoltaic effects.

Most modern photovoltaic devices employ a P-N junction in a semiconductor. The photovoltaic effect also appears at a function between a metal and a semiconductor; in fact, many early photovoltaic devices employed such a metal-semiconductor junction. A common type is the junction between iron and the semiconductor selenium. Such devices found great utility as photovoltaic cells and were used to turn on street lights automatically when darkness fell. Since the applications of optical energy measurement and energy conversion usually employ semiconductor photovoltaic materials, the emphasis in this module will be upon semiconductors.

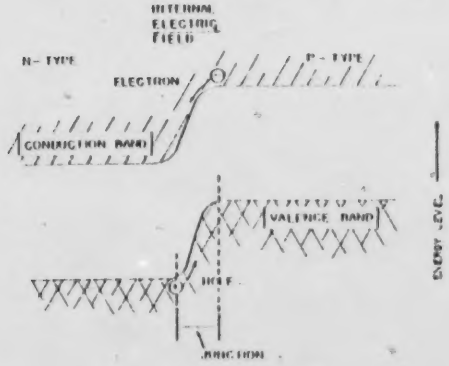



FIG. 2

The photovoltaic effect depends upon distortion of the energy band structure through a P-N junction (Figure 2). Height of the conduction band and valence band change through the junction region from N-type material to P-type material. Thus, an electron in the P-type material will move along the bottom of the conduction band, as shown. Similarly, a hole near the top of the valence band in the N-type material will also move as shown. Thus, the junction acts very similarly to a built-in electrical field, causing the motion of the electrical charge.

Thus, when P-type and N-type semiconductors form a junction, a voltage is produced across the junction, which will separate holes and electrons. However, there usually are no free holes and electrons in

and electrons in the immediate vicinity of the junction to allow electrical current to flow. If, however, light is incident upon the junction and is absorbed, the light energy will produce free holes and electrons, which then are capable of moving under the action of the electric field (Figure 3).

Absorption of light energy in the vicinity of the junction thus creates current carriers, which are separated by the built-in electric field. If electrical contacts are attached at the surface on the two sides and connected through a load resistor as shown, there will be a net flow of electrical current through the load resistor and, therefore, generation of electrical power.

This generation is the photovoltaic effect — direct generation of electrical energy by absorption of light energy in the vicinity of a P-N junction in a semiconductor. No external voltage must be applied to produce the photovoltaic effect.

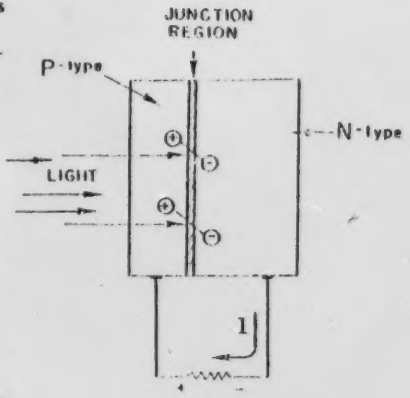



FIG. 3

## OTHER PHOTOSENSITIVE DEVICES

There are several other optical-electrical effects that rely upon absorption of optical energy and through which current may be generated in an external load resistor. Some examples are the "photoemissive effect" and the "photoconductive effect." Energy converters and optical sensors based upon these effects also have been developed. Both of these effects require an external voltage applied to the materials.

# OPERATIONAL CHARACTERISTICS OF SILICON PHOTOVOLTAIC DEVICES

## CONSTRUCTION AND ELECTRICAL CIRCUITS

The circuit employed for photovoltaic devices is illustrated in Figure 4. The light (arrows) is incident on the photodetector, shown schematically as a diode. Current I flows as shown, and the voltage is generated across the load resistor $R_L$. Voltage is given by Ohm's law (Equation 1).

$$V = IR_L \qquad (1)$$

where

V = voltage.
I = current.
$R_L$ = load resistor.

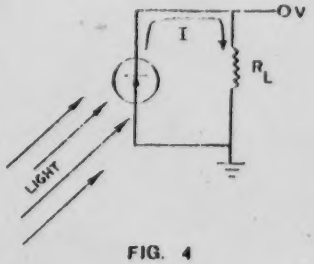



FIG. 4

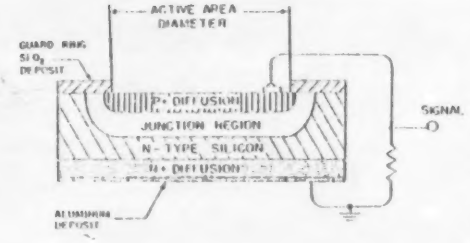



FIG. 5

Structure of a typical silicon photovoltaic device is displayed in Figure 5. A piece of N-type silicon is used as the starting material. Impurities are diffused into one side to form a P-type region and a junction. Other materials can be diffused into the opposite side to produce a heavily-doped N-type region for ease in making an electrical contact. A guard-ring structure of $SiO_2$ is deposited on the surface to reduce stray current leakage. Electrical contacts (aluminum) are deposited on the surface. Fabrication of such devices has become a well-developed technology.

## RESPONSIVITY

The response of the P-N junction to light is represented by the response curve in Figure 6. For relatively low values of the load resistor, response — that is, externally generated current — is approximately a linear function of the incident light energy. For large values of the load resistor, the response will saturate, as indicated. Response will saturate when the voltage drop across the load resistor becomes equal to the value of built-in voltage at the junction. Thus, the voltage drop has a maximum value, equal to the product of the current and the resistance. Therefore, for larger values of resistance, there is a maximum limiting current that can be generated.

The photovoltaic effect also can be used in the form of a sensor that generates a measured voltage across an open circuit. The sensor is less important as an energy converter than some other applications because it requires the development of electrical power and, therefore, the flow of electrical current, in the external circuit.

Figure 6, defines an important parameter of the photovoltaic detector — namely, "responsivity," which is the amount of current that flows in the external circuit divided by the optical input

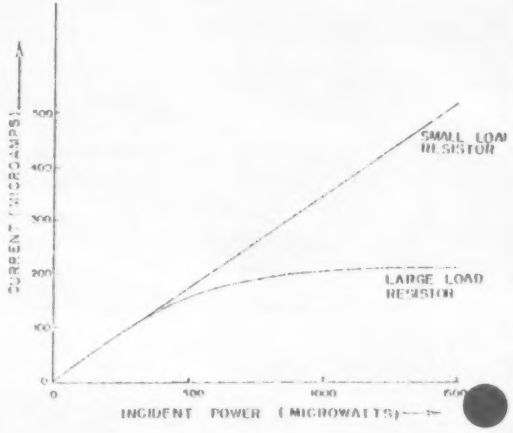



FIG. 6

power. It has units of current per unit power and is given by the quotient of the current divided by the power. For the example shown in Figure 6, responsivity is equal to 210 microamps divided by 600 microwatts, or 0.35 microamps per microwatt. This is a typical value characteristic of modern photovoltaic cells based upon silicon P-N junctions.

## EFFICIENCY

Current generated by absorption of light delivering power absorbed by the junction is given by Equation 2.

$$I = RP \tag{2}$$

where

R = responsivity.
P = power in watts.

Since electrical power generated will be IV, with V, voltage, given by $IR_L$, the efficiency (ratio of electrical power to light power) can be expressed as in Equation 3.

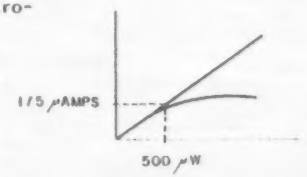
$$\text{Efficiency} = \frac{IV}{P} = \frac{I^2R_L}{P} = \frac{R_2P_2R_L}{P} = R_2PR_L \tag{3}$$

Notice that efficiency cannot be increased very much by an increase of $R_L$, because of saturation effects shown in Figure 6 when a large resistor is used. A calculation using Figure 6 is given in Example A.

**EXAMPLE A: CALCULATION OF CURRENT AND VOLTAGE IN A PHOTOVOLTAIC CELL**

Given: Light is incident upon a photovoltaic cell that has characteristics shown in Figure 6. The load resistor, as in Figure 5, is 100 Ω. Optical power is 500 microwatts.

Find: (a) Current I and (b) voltage V.




Solution: (a) The resistor is a relatively small one; therefore, from the upper curve in Figure 6, current I is read as 175 microamps at 500 microwatts optical power.

(b) Use Ohm's law (Equation 1):

$V = IR_L$

$= (175 \times 10^{-6})(100)$

$V = 1.75 \times 10^{-2}$ volts.

## SPECTRAL RESPONSE

Spectral response of silicon is plotted in Figure 7. This graph shows response of silicon photovoltaic devices as a function of the wavelength of the incident light. (A full discussion of the concept of wavelength of light will be developed in Concept Module 13-0.) The reason for the shape of this curve is beyond the scope of this module. We simply point out that silicon detectors are most useful in the visible portion of the spectrum (0.4 to 0.7 micrometers), and in the near-infrared portion of the spectrum (0.7 to 0.9 micrometers). Other materials exhibit a strong response farther into the infrared and, therefore, have applicability as detectors for longer-wavelength infrared radiation, to which silicon detectors would not respond.

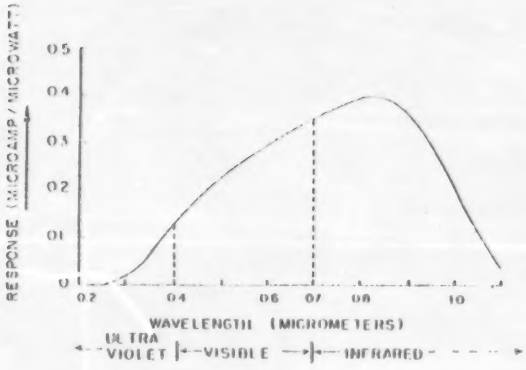



FIG. 7

## OTHER DEVICES USING DIFFERENT SEMICONDUCTOR MATERIALS

A number of different types of semiconductors have been employed, including silicon, gallium arsenide, indium phosphide, cadmium telluride, gallium phosphide, and cadmium sulfide. Some of the other materials have a higher theoretical efficiency than silicon, which has a maximum theoretical efficiency of approximately 20%. However, for large-scale applications, where low cost is a factor, silicon now is the most practical candidate. Some of the other materials can be used as detectors of infrared radiation.

# APPLICATIONS

## SENSORS

As previously mentioned, photovoltaic energy converters are used to turn street lights on and off automatically. They also

are commonly employed as quantitative detectors of the amount of optical radiation. Thus, they have application in camera light meters, photometers (used to measure illumination levels), colorimeters (used to measure color values of paints, fabrics, etc.), and infrared detectors (used in night-vision devices and in medical sensors). They can be used as electric eyes (which could be employed to open doors automatically, or as burglar alarms), as flame sensors (fire alarms and furnace controls) and as liquid-level sensors.

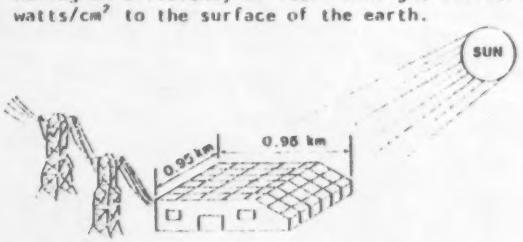
## ELECTRICAL POWER GENERATION

As energy converters, used for direct generation of electrical energy from sunlight, photovoltaic converters have been employed for a number of years on satellite systems to provide electrical energy for satellite operation. These are the solar cells that have been employed on many satellites and space probes. Such cells have not found much application in direct generation of electricity from sunlight on the earth's surface, because of the relatively high cost of the material. High cost has not been a great drawback for space applications because total areas involved are small and because the very specialized application will tolerate a higher cost per unit of electrical power. For generation of larger amounts of electrical power on the earth's surface, however, the cost will have to be reduced considerably. If the cost of silicon photovoltaic cells could be reduced to the approximate region of $0.50 per watt of electrical generating capacity, they could be competitive on the earth's surface for direct generation of electricity from sunlight. By the mid-1980's, the refinement of silicon technology probably will allow this cost reduction; therefore, within the 1980's the direct use of photovoltaic energy converters to produce electricity on the earth's surface may be a reality.

Example B shows the calculation for the size of a photovoltaic cell unit used in a generating station.

**EXAMPLE B: CALCULATION OF THE SIZE OF A SOLAR CELL UNIT FOR A GENERATING STATION**

Given: A solar electrical generating station based upon photovoltaic energy converters uses silicon solar cells having an efficiency of 10%. Sunlight delivers 0.11 watts/cm$^2$ to the surface of the earth.



Find: Size of the area that must be covered by the solar cells for a 100-megawatt generating station.

Solution: The solar power to be collected is $1000 \times 10^6$ watts (100 megawatts divided by 10% efficiency). This much power will require an area of $1000 \times 10^6 \div 0.11 \approx 9.1 \times 10^9$ $cm^2$, which would require a square area about $9.5 \times 10^4$ cm (0.95 km) on a side to be covered by the silicon solar cells. Notice that the station will be operative only when the sun is shining.

## SUMMARY

Photovoltaic materials are semiconductor devices (P or N) that convert light energy into electrical energy. Some combinations of semiconductor materials deposited upon metal plates can generate voltage at the junctions when exposed to light radiation. Voltage is generated at junctions (barrier layers) between the two types of materials when radiant energy is absorbed. This process is termed the "photovoltaic effect."

## EFFICIENCY OF A PHOTOVOLTAIC DEVICE

### MATERIALS

Photovoltaic detector (e.g., United Detector Technology Model PIN-10DP).
Helium-neon laser (about 1-2 mW, e.g., Spectra-Physics Model 132) or other low-power light source.
Resistors - 100 Ω and 10,000 Ω.
Milliammeters.
Wire for electrical connections.
Laser power meter (e.g., Spectra-Physics Model 401C).
4 — Neutral density filters (e.g., Kodak Wratten filters having optical density of approximately 0.3).
Graph paper.

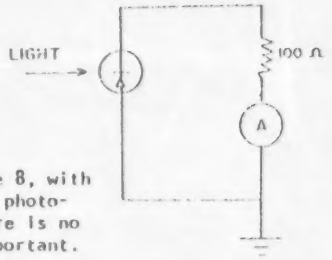



FIG. 8

### PROCEDURE

1. Connect photovoltaic device as illustrated in Figure 8, with the 100-Ω load resistor and ammeter in series. The photovoltaic device is shown as a diode; but because there is no externally-applied voltage, polarity will not be important.

2. CAUTION: Do not look directly into laser beam. Do not allow beam to reflect from a shiny object into eyes. Turn on the HeNe laser. Direct beam into laser power meter, and measure power. Insert neutral-density filters between laser and power meter. Measure power transmitted through different numbers of neutral-density filters. Enter values in Data Table.

3. Remove filters and power meter. Direct beam to strike photovoltaic detector. Make sure that beam falls entirely on active area of detector. Measure current on milliammeter.

4. Add neutral-density filters one by one, repeating Step 3, and measure current in each case. Enter values in Data Table.

5. Replace 100-Ω resistor with 10,000-Ω resistor. Repeat procedure in Steps 3 and 4.

6. Plot results obtained in Steps 3, 4, and 5 on graph paper. Plot measured current versus incident light power for the

two values of load resistance.

7. From the 100-Ω resistor data, calculate responsivity (microamps/microwatt).

8. From value in Data Table for the 100-Ω resistor and no neutral-density filters, calculate efficiency of conversion of optical energy into electrical energy for this experiment. Remember, electrical power (in watts) is equal to square of current (in amperes) times load resistance (in ohms).

9. Why is the shape of the curve different for the two different resistors?

| DATA TABLE | | | |
|---|---|---|---|
| No. of Neutral Density Filters | Laser Power Transmitted | Current (100 Ω Resistor) | Current (10,000 Ω Resistor) |
| 0 | | | |
| 1 | | | |
| 2 | | | |
| 3 | | | |
| 4 | | | |

## SELF CHECK

1. Describe operation of photovoltaic devices.

2. Describe at least two applications of photovoltaic materials.

3. Suppose a photovoltaic detector has a responsivity of 0.5 microamps per microwatt and that 10 milliwatts of light energy are absorbed by the device. What is the resulting electrical current if the device is connected across a load resistor of small resistance?

4. Given results of 3 above, with a load resistance of 120 Ω,

what is the efficiency of conversion of light energy into electrical energy?

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UNIFIED TECHNICAL CONCEPTS

MODULE 9 T 1

BOILERS

# THERMAL APPLICATION OF ENERGY CONVERTORS

Technical Education Research Center - Southwest

TERC - SW

## INTRODUCTION

Generation of steam from water in a boiler provides energy conversion from the thermal energy of burning fuel to the potential and kinetic energy of high-temperature, high-pressure steam. All electrical generating plants that produce electrical energy from thermal energy employ steam generators in the energy conversion process. The heat source may be the combustion of a chemical fuel such as coal, gas or oil, or nuclear or solar energy; but in each case, the energy is transfered to high-pressure steam used to turn a turbine, which in turn drives an electric generator. The latter energy conversion systems are explained in other modules. This module discusses the energy conversion from hot combustion gases to pressurized steam in a boiler. In the laboratory, the student will determine the effects of preheated water and of ash deposits upon steam generation.

## PREREQUISITES

Student should have completed Module 9-0, "Energy Converters."

## OBJECTIVES

Upon completion of this module, the student should be able to:

- Draw and label a simple diagram of a steam generator.
- Explain in a short paragraph how thermal energy is transferred in a steam generator. Include the importance of radiation, convection in combustion gases and water, and conduction through water tubes.
- Identify three types of thermal losses in a steam generator.
- Explain how each of the following design features of modern steam generators reduces heat losses:

Closed water system.
Thermal insulation.
Preheater (economizer).
Superheater.
Air heater.
Stud tubes.
Purified water.
Clean combustion.

- Draw and label a diagram of a two-drum steam generator showing the following parts:

  Air heater.
  Economizer.
  Superheater.
  Water tubes.
  Upper and lower drums.
  Furnace.

- Given the appropriate equipment, experimentally determine the effects of using preheated water and the effects of ash deposits on steam generation.

## DISCUSSION

A steam generator is a device for producing high-pressure, high-temperature steam from low-pressure liquid water by the application of thermal energy. This module discusses the transfer of thermal energy within the steam generator and methods of improving the efficiency of this energy transfer.

Figure 1 is a diagram of a simple steam generator, in which thermal energy is produced by the combustion of a fuel. This energy is transferred to thermal energy of water to produce steam. Thermal energy moves within the system by three processes:

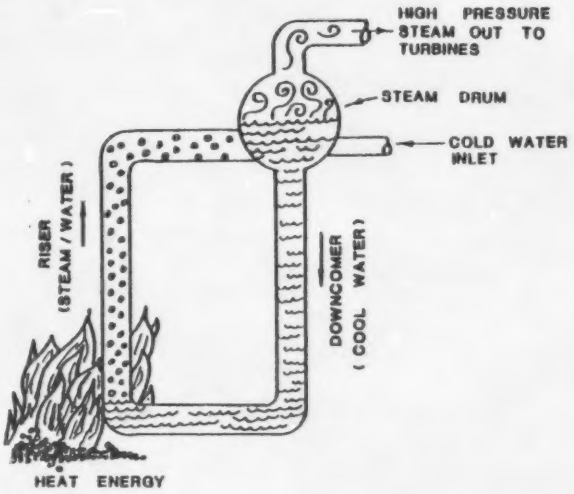



FIG. 1

- Thermal radiation from the heat source and from the internal walls of the furnance is absorbed by pipes carrying water and steam.
- Convection currents heat the water pipes by bringing hot combustion gases into contact with the pipes. Convection within the water flow system also carries cool water downward in the system and heated steam upward into a steam drum.
- Heat energy is conducted through the walls of the water tubes to heat water and steam.

Greatest efficiency is achieved when each of these processes is utilized to transfer the maximum amount of heat energy from combustion products to the water.

### ENERGY LOSSES

Thermal energy leaves the steam generator in three ways:

- Part of the heat energy produced by the combustion process remains in the exhaust gases and is discharged through the exhaust port.

Some thermal energy escapes through furnance walls and pipes to heat the environment around the steam generator. The remainder of the energy leaves the generator in the form of heated steam. This energy is applied to turn turbines, but some of it remains as thermal energy in the hot water and low-pressure steam discharged from the turbines.

High-efficiency transfer of energy from the combustion process to the turbine requires that each of the energy losses is minized.

## MODERN BOILER DESIGN

Figure 2 shows a modern two-drum boiler for steam generation. Heat losses are reduced throughout the system by thermal insulation. The efficiency of this system is increased by operating it as a closed water-flow system. The low pressure steam leaving the turbines (not shown) is condensed to liquid water in a heat exchanger, but the temperature of water from the heat exchanger remains near the boiling point. Thus, the input water to the steam generator contains a portion of the thermal energy that left the generator earlier as steam. Less energy is necessary to produce steam from this hot water than from cold input water.

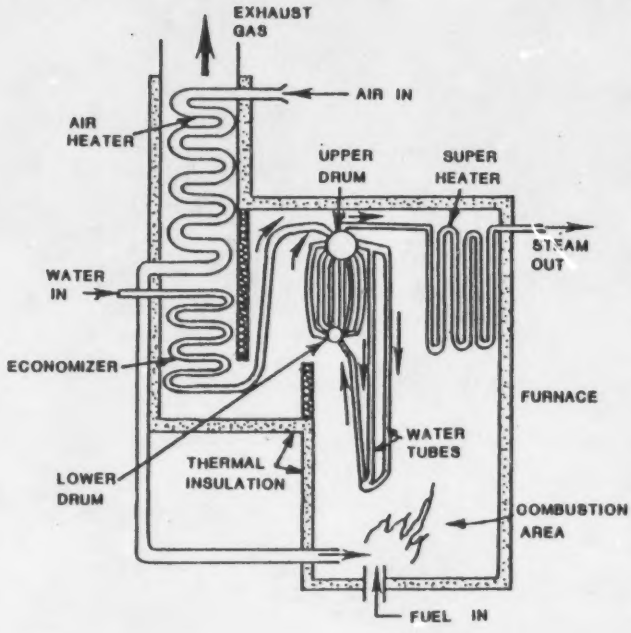



FIG. 2

Air for the combustion process is also heated before it enters the combustion area. The air heater is located in the coolest part of the steam generator and absorbs heat energy that remains in the exhaust gases after heat transfer to the water system has been completed. This heat energy is returned to the combustion area with the input air.

Thermal transfer to water occurs in three sections of the steam generator. Input water passes through a preheater called an economizer, located in the exhaust port

just below the air heater. This process raises the temperature of the water almost to the boiling point and reclaims heat energy that otherwise would have been lost in the exhaust gas.

The boiler consists of two large drums connected by water tubes. Heated water flows down some of these tubes by convection, and steam flows upward in others. Water tubes present a large surface area for heat transfer. In many modern boilers, the complete inner surface of the furnace is lined with water tubes that provide the necessary area for efficient heat transfer and prevent thermal damage to the walls.

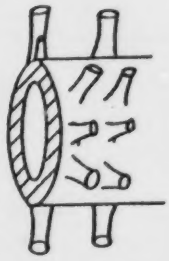


FIG. 3

Steam collects in the upper drum of the boiler and flows out the steam generator through a superheater located in the hot-test part of the furnace. This heat exchanger increases the temperature of output steam to the desired level.

Heat transfer to water tubes is increased at some points in the boiler and supercharger by use of stud tubes shown in Figure 3. These stud tubes present larger surface areas to the hot gases. Figure 4 shows two conditions that can reduce the efficiency of the heat transfer through water tubes. Scale formed on the tube inner surface from water impurities and ash deposits on the outer surface act as heat barriers. For these reasons, impurities must be removed from water used in the steam generator, and the combustion process must be as clean as possible.

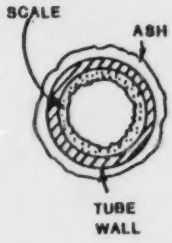



FIG. 4

## EFFICIENCY

Fuels burn with various efficiencies. For example, bituminous coal, with a heating value of 13,500 Btu/lb, burns with about 85-90% efficiency. When all energy losses are taken into account, the overall steam generator plant efficiency is from 25% to 30%.

## SUMMARY

Boilers convert the thermal energy of burning fuel into the potential and kinetic energy of steam. Steam is passed through turbines to produce mechanical rotational energy. Boilers produce steam when a furnace applies heat to water. Modern boilers contain devices that increase efficiency; for example, insulation, closed-flow water systems, pre-heated air, etc.

## EFFECTS OF PREHEATED WATER AND ASH DEPOSITS UPON STEAM GENERATION

### MATERIALS

Steam engine kit (Edmund Scientific Company or equivalent).
Dry fuel tablets.
Candle.
Timer.

### PROCEDURES

1. Fill boiler (Figure 5) about half full with cold water.
2. Open valve.
3. Place fuel tablet in holder; light fuel tablet, and place holder with burning fuel under boiler. Start timer.
4. When steam begins to escape through valve, close valve and rotate flywheel. Continue to rotate flywheel until steam engine runs without assistance. Stop timer. Record in Data Table heating time for cold water.
5. Remove fuel, and extinguish fire. Allow steam engine to cool for five minutes.
6. Place new fuel tablet in holder and repeat above procedure. Record heating time for hot water.

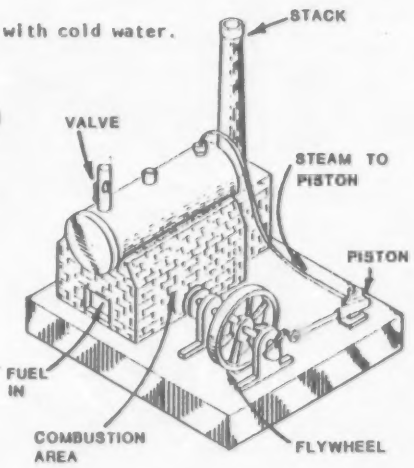



FIG.5

7. Replace fuel tablet with small candle, and establish generation of steam engine. Observe engine for five minutes and note changes in rotational rate as carbon deposit forms on boilers.
8. Remove candle and allow engine to cool. Remove carbon deposits, and empty remaining water from boiler.
9. Answer the questions presented in the Data Table.

| DATA TABLE |
| --- |
| Heating time for cold water = _____.<br>Heating time for hot water = _____.<br>What conclusions can be formed about the use of preheated water?<br><br>How did rotational rate change as carbon deposit formed from candle flame?<br><br>What conclusions can be formed about the relationship of clean combustion to efficiency? |

## SELF CHECK

1. Draw and label a diagram of a simple steam generator.

2. Explain how each of the following contributes to heat transfer in a steam generator:

   a. Thermal radiation from the heat source.
   b. Convection currents in combustion products.
   c. Convection currents in water and steam.
   d. Conduction of heat through walls of water tubes.

3. Explain the three loss factors that lower the efficiency of steam generators using combustion as a heat source.

4. Identify the parts of the steam generator in the figure on the next page.

   A._____.
   B._____.
   C._____.

D. _____.

E. _____.

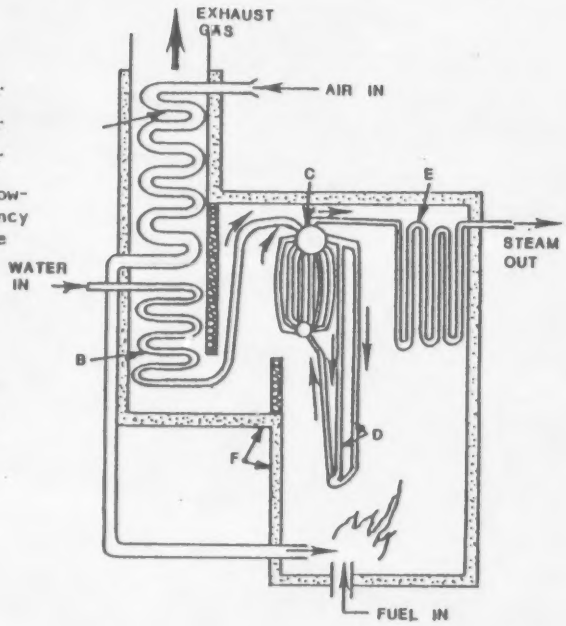
F. _____.

5. Explain how each of the following would effect the efficiency of the steam generator in the figure to the right:

   a. Eliminate part A.
   b. Eliminate part B.
   c. Eliminate part E.
   d. Eliminate part F.

6. Explain how heat transfer is aided by use of each of the following:

   a. Stud tubes.
   b. Purified water.
   c. Clean combustion.

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UNIFIED TECHNICAL CONCEPTS

MODULE 9 T 2

THERMOELECTRIC GENERATORS

THERMAL APPLICATION OF ENERGY CONVERTORS

Technical Education Research Center - Southwest

TERC - SW

# INTRODUCTION

## THERMOELECTRIC GENERATORS

This module explores thermoelectricity, the direct conversion of heat energy into electrical energy (or the reverse) by means of three related physical phenomena — the Seebeck effect, the Peltier effect, and the Thomson effect. Thermoelectric effects are exhibited by both metallic conductors and by semiconductors. The magnitude of the effects is larger in semiconductors; therefore, semiconductors generally are used as practical thermoelectric generators, which, in turn, are used to produce electricity directly from heat. In the laboratory, the student will set up a simple thermoelectric apparatus and will measure the thermoelectric voltage generated for both metallic conductors and for semiconductors.

# PREREQUISITES

Student should have completed Concept Module 9-0, "Energy Converters."

# OBJECTIVES

- Upon completion of this module, the student should be able to:
- Describe the Seebeck effect, the Peltier effect, and the Thomson effect.
- Name two general types of thermoelectric materials, and give at least one specific example of each.
- Name at least four applications of thermoelectricity.
- Given the necessary information about materials, calculate the thermal EMF generated in a specific arrangement.
- Given the necessary information, calculate the efficiency of a thermoelectric generator.

- Given the necessary materials and equipment, set up thermoelectric systems; and measure thermoelectric coefficients for both metallic conductors and semiconductors.

## DISCUSSION

Thermoelectricity is the direct conversion of heat energy into electrical energy (or the reverse; that is, direct conversion of electrical energy into heat). Thermoelectric effects are observed in electrically-conducting materials through which electrical current flows. There are two broad classes of electrical conductors that show thermoelectric effects; they are metals and semiconductors. Thermoelectric effects in semiconductors are larger than in metals, so that semiconductors are used in practical thermoelectric power generators.

There are three related thermoelectric effects: the Seebeck effect, the Peltier effect, and the Thomson effect.

### THE SEEBECK EFFECT

When two different conductors are joined in a loop, and when a temperature difference exists between the junctions at which the conductors are joined, an electromotive force (EMF) is produced. This EMF is called a "thermoelectric EMF," or a "Seebeck EMF." The situation is sketched in Figure 1. The two different conductors — for example, wires of two different metals — are joined at their two ends. When the junctions are at different temperatures, $T_1$ and $T_2$, as shown, a voltage V is produced between points A and B. A voltage-measuring device can be inserted between A and B. As long as the temperature at points A and B is the same, the thermoelectric voltage V will not be affected.

FIG. 1

The thermoelectric voltage, or EMF, is expressed by Equation 1.

$$V_s = (S_1 - S_2)\ (T_1 - T_2) \qquad (1)$$

where

$V_s$ = Seebeck voltage, or net thermal EMF set up in a thermocouple.
$S_1$ = constant of conductor one.
$S_2$ = constant of conductor two.
$T_1$ = temperature at first junction.
$T_2$ = temperature at second junction.

The constant S for a material is called the "Seebeck coefficient" for the material. The Seebeck coefficient is dependent upon the temperature and may be either positive or negative. With reference to Figure 1, if $T_1 > T_2$ and the EMF has the indicated polarity, then $S_1 > S_2$. If the direction of the temperature gradient is reversed, the sign of the EMF also will be reversed.

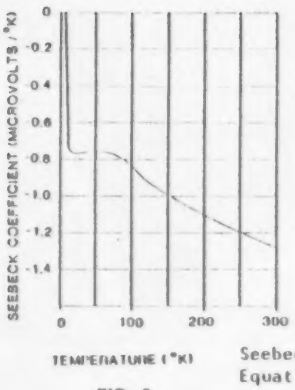


FIG. 2

According to Equation 1, if one measures the EMF and the temperature difference $(T_1 - T_2)$, one obtains $(S_1 - S_2)$, the difference in the Seebeck coefficients for the two materials. In order to obtain the individual coefficients, one makes measurements in which one of the materials is a reference material for which S is known. By convention, lead has been chosen as a standard reference material. The value of the Seebeck coefficient for lead is sketched in Figure 2 for temperatures from 0 to 300 K. The Seebeck coefficient varies rapidly at low temperatures, and becomes zero for temperatures below 10 K. The sign of the Seebeck coefficient for lead is negative.

Thus, to measure the Seebeck coefficient for a conductor, one may join the ends of the conductor to a reference conductor made of lead, as shown in Figure 1, and measure voltage and the temperature difference $(T_1 - T_2)$. Then the Seebeck coefficient for the unknown material can be found from Equation 1, by use of the known value for lead.

According to Equation 1, the voltage generated when two different materials are used in a thermoelectric circuit depends upon the difference $(S_1 - S_2)$, called the "thermoelectric power" for this combination of two different materials.

## THE PELTIER EFFECT

The Peltier effect involves the heating and cooling of the junctions between two different conductors connected in a loop when an electric current flows in the loop. With reference to Figure 3, if the temperatures of the junctions are not permitted to change, the Peltier heat per unit time is released at the upper junction and absorbed at the lower junction. The Peltier coefficient $\pi$ is defined by Equation 2.

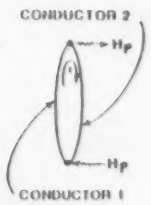


FIG. 3

$$H_p = (\pi_1 - \pi_2)I \qquad (2)$$

where

$H_p$ = Peltier heat released at upper junction and absorbed at lower.
$\pi_1$ = Peltier coefficient for conductor one.
$\pi_2$ = Peltier coefficient for conductor two.
$I$ = current.

The effect is reversible; that is, if the direction of I were reversed, heat would be released at the lower junction and absorbed at the upper junction. For the direction of current flow as shown in Figure 3, with heat released at the upper junction, one would have $\pi_1 > \pi_2$.

The release of heat at one of the junctions leads to heating of the surroundings. The absorption of heat at one of the junctions leads to cooling of the surroundings. Thus, the Peltier effect can be used for either heating or for cooling.

## THE THOMSON EFFECT

The Thomson effect is shown (Figure 4) as the release of heat from a single conductor in which a current is flowing, and in which a temperature gradient exists. The heat released is given by Equation 3.

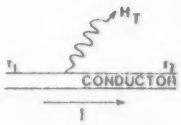

FIG. 4

$$H_T = \mu I (T_1 - T_2) \qquad (3)$$

where

$H_T$ = Thomson heat.
$\mu$ = Thomson coefficient for conductor.

The effect is reversible; if the direction of current flow is reversed, then heat will be absorbed instead of released. The sign $\mu$ may be either positive or negative, depending upon the material. If $T_1 > T_2$, and if heat is released for the direction of current flow as shown in Figure 4, then $\mu > 0$.

The Thomson thermoelectric effect must be distinguished from ordinary resistive heating as given by $I^2R$, where R is the electrical resistance of the conductor. The $I^2R$ heating is also present, of course, but its sign does not change as the direction of current flow changes. The Thomson thermoelectric effect is a different effect, which either can release or absorb heat in a conductor in a region of variable temperature.

These three thermoelectric effects are all related, and the coefficients for the Seebeck, Peltier, and Thomson effects are connected by two equations. The first of the equations is Equation 4, which can be stated as follows:

$$S = \frac{\pi}{T} \qquad (4)$$

Equation 4 relates the absolute temperature T and the Seebeck and Peltier coefficients. The second equation, which will not be presented here, is more complicated and depends upon a knowledge of differential calculus. This second equation relates the Seebeck and Thomson coefficients.

Thus, all three coefficients are related. If one coefficient is known, the other two may be determined by means of the two equations. For simplicity, the Seebeck coefficient usually is

measured; then the Peltier and Thomson coefficients are derived from it. A simplified example involving a calculation of the Seebeck and Peltier effects is given in Example A.

**EXAMPLE A: CALCULATION OF SEEBECK AND PELTIER COEFFICIENTS**

Given: A thermocouple is set up as shown in Figure 1, with lead as conductor 2. $T_1 = 305$ K and $T_2 = 295$ K; and the observed voltage V, polarized as shown in Figure 1, is 30 μ volts.

Find: (a) The Seebeck coefficient of conductor 1.
(b) The Peltier coefficient of lead at 300 K.

Solution: (a) From Equation 1:

$$(S_1 - [-1.28])(305 - 295) = 30\ \mu\text{ volts}$$

$$(S_1 + 1.28)(10) = 30\ \mu\text{ volts}$$

$$S_1 = 3 - 1.28$$

$$S_1 = 1.72\ \mu\text{ volt/K}$$

(b) Near 300 K, the Seebeck coefficient of lead is -1.28 μ volt/K, from Figure 2. From Equation 4:

$$\pi = S\ T$$

$$= (-1.28)(300)$$

$$\pi = -384\ \mu\text{ volt}$$

## EFFICIENCY

The usefulness of a particular material for thermoelectric applications depends, not only upon its thermoelectric coefficient, of course, but also upon other material properties. For a good thermoelectric generator, the Seebeck coefficient should be large; but the electrical resistivity and thermal conductivity should be low. These competing demands lead to the concept of a "figure of merit" that combines all three properties and that expresses the utility of a material for thermoelectric applications. The figure of merit for a material is given by Equation 5.

$$Z = \frac{S^2}{\rho k} \qquad (5)$$

where

$Z$ = the figure of merit for a material.
$S$ = Seebeck coefficient.
$\rho$ = electrical resistivity.
$k$ = thermal conductivity.

The figure of merit is useful in comparing different materials for thermoelectric applications. Some values will be given later in the description of materials. For semiconductors, Z may be in a range of about 0.001.

A thermoelectric generator, of course, utilizes two different materials. The expression for the figure of merit for the two materials used in combination is more complicated than that indicated in Equation 5; but it still combines the properties of Seebeck coefficient, electrical resistivity, and thermal conductivity for the two materials.

The figure of merit also is important because it affects the efficiency of a generator. The efficiency of a thermoelectric generator is the ratio of the electrical power to the rate of heat supply from the hot source. It expresses the fraction of heat energy converted to electrical energy. The maximum efficiency that can be obtained from a thermoelectric generator working between a heat source at temperature $T_1$ and a heat sink at a lower temperature $T_2$ is indicated by Equation 6.

$$\eta_{max} = \left(\frac{T_1 - T_2}{T_1}\right)\left(\frac{M - 1}{M + T_2/T_1}\right) \qquad (6)$$

where

$\eta_{max}$ = maximum efficiency obtainable from a thermoelectric generator.
$M = [1 + Z(T_1 + T_2)/2]^{1/2}$.

Some values of efficiency calculated with the aid of Equation 6 are shown in Figure 5 for several values of the figure of merit Z. The efficiency is plotted versus the temperature $T_1$ of the hot junction, for constant temperature $T_2$ = 300 K. For reasonable values of Z and $T_1$, efficiencies between 20% and 30% can be obtained.

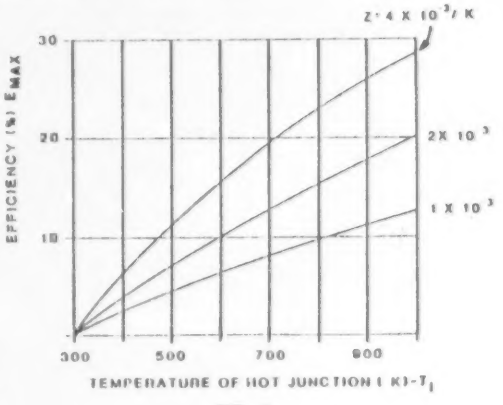

FIG. 6

The value of the efficiency given by Equation 6 is obtained only when the electrical resistance of the circuit is properly adjusted for optimum efficiency. The details for the proper adjustment are not presented here; however, the student should note that without such adjustment, the efficiency will be lower than the maximum value given by Equation 6.

## CONSTRUCTION OF THERMOELECTRIC DEVICES

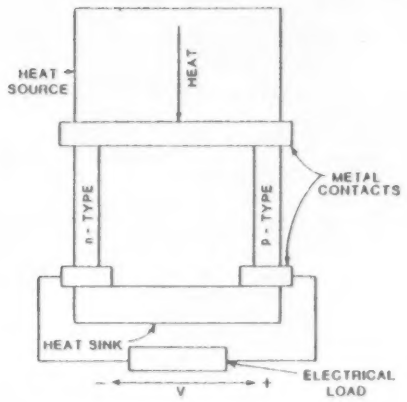


FIG. 6

Now the construction of some thermoelectric generators shall be considered. Semiconductors exhibit larger thermoelectric effects and more complexity than metals. An electrical generator often is constructed of p-type and n-type semiconductor material (Figure 6). The Seebeck coefficient is positive for the p-type material, and negative for the n-type material. Thus, if $S_2$ corresponds to the n-type material, the term $(S_1 - S_2)$ will be large in magnitude (because subtraction of the negative $S_2$ is the same as the addition of a positive value). Heat flows in from the heat source to the metal contact at the top, and is removed by the heat sink at the bottom. A temperature difference is established, and a voltage is generated in the external circuit, as indicated. This assembly, therefore, can generate electricity directly from the flow of thermal energy.

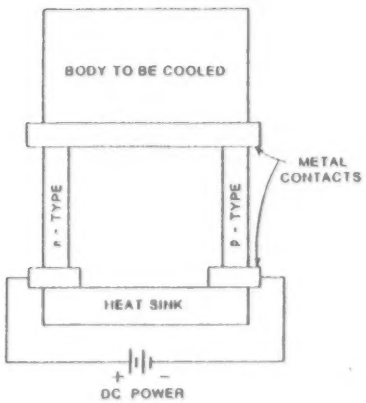


FIG. 7

Thermoelectric effects also can be used for heating or for cooling, by virtue of the Peltier effect. Figure 7 illustrates a simple thermoelectric cooler, also utilizing semiconductors. With the current flow as shown, heat is withdrawn from the top junction, which is cooled. If the direction of heat flow were reversed, the top junction would be heated.

The basic elements displayed in Figures 6 and 7 often are combined in modules in which individual elements are connected in series electrically and in parallel thermally, as in Figure 8. This configuration allows development of coolers that have large areas, but that use only small currents.

When the required temperature difference for a Peltier cooler becomes large, stages frequently are cascaded (Figure 9). Then the hot junction of the first stage becomes the cold junction for the second stage. This arrangement allows the production of larger temperature differences than would be possible in a single-stage device.

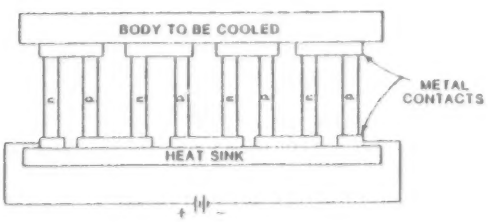


FIG. 8

## THERMOELECTRIC MATERIALS

Metals and semiconductors are the two broad classes of conducting materials used for thermoelectric applications.

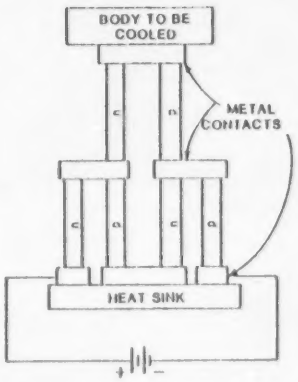


FIG. 9

### METALS

Metals are convenient to use in wire form and, hence, are easier to fabricate into thermoelectric elements than are semiconductors. A thermocouple can be formed simply by soldering together the ends of two wires of different metals. The electrical leads are the wires themselves.

However, metals have relatively low values of Seebeck coefficient. Typical values lie in the range of microvolts per degree. These values are large enough to permit the use of metallic thermoelectric elements as thermocouples for temperature measurement, but are too small to allow metals to be efficient thermoelectric power generators.

There are a number of combinations of metals and alloys used in science and industry for temperature measurement. Table 1 lists some widely-used combinations. These combinations are chosen to have relatively large values of thermoelectric power; that is, of $S_1 - S_2$, as defined in Equation 1. The values of thermoelectric power range up to several tens of microvolts per degree (dependent upon temperature). Combinations of metals are available to cover various temperature ranges, as indicated in Table 1.

TABLE 1. METALS USEFUL FOR THERMOCOUPLES

| Metal | Useful Temperature Range | Approximate Thermoelectric Power |
|---|---|---|
| Copper-Constantan[a] | -188°C to 350°C | 15 - 60 μV/°C |
| Iron-Constantan[a] | 200°C to 800°C | 55 μV/°C |
| Platinum-Platinum + 10% Rhodium | 0°C to 1500°C | 6 - 12 μV/°C |
| Chromel-Alumel[b] | 500°C to 1200°C | 40 μV/°C |

[a] Constantan is 55% copper and 45% nickel.

[b] Chromel is 90% nickel and 10% chromium; Alumel is 94% nickel, 3% manganese, 2% aluminum, and 1% silicon.

## SEMICONDUCTORS

Semiconductors have much larger values of thermoelectric power than metals. Values range up to millivolts per degree, compared to a few microvolts per degree for metals. Thus, semiconductors are suitable for use in thermoelectric power generation and in thermoelectric coolers.

Semiconductors are not fabricated easily into wires and, thus, are less convenient to use than metals. Semiconductors are used in rod-or-bar form, and electrical lead wires must be attached.

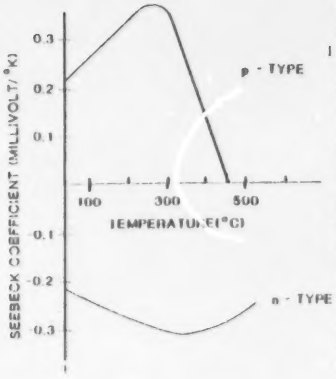


FIG. 10

One of the most widely-used semiconductor materials is lead telluride, which is a compound of the chemical elements lead and tellurium. Its chemical symbol is PbTe. The Seebeck coefficient for lead telluride is presented in Figure 10. The values in Figure 10 are for specific levels of impurities in the material; because the values of Seebeck coefficient are dependent upon the impurities in the material, these values must be considered as approximate. The Seebeck coefficient is positive for p-type material and negative for n-type material; therefore, a thermoelectric circuit can be formed from p-type and n-type PbTe. The thermoelectric power, $S_1 - S_2$, may be as large as 0.6 millivolts/degree at temperatures near 200°C.

There are a number of other semiconductor materials that can be used as thermoelectric elements. Some of these are listed in Table 2, along with representative values of the Seebeck coefficient. This table shows some of the materials that could be employed as thermoelectric generators.

TABLE 2. VALUES OF SEEBECK COEFFICIENT FOR SEMICONDUCTORS

| Material | Seebeck Coefficient (mV/K) | Temperature (°C) |
|---|---|---|
| Zinc Antimonide (ZnSb) (p-type) | 0.25 | 327 |
| Bismuth Telluride ($Bi_2Te_3$) (p-type) | 0.265 | 20 |
| Indium Antimonide (InSb) (n-type) | -0.35 | 20 |
| Indium Antimonide (InSb) (p-type) | 0.80 | -173 |

| | | |
|---|---|---|
| Lead Selenide (PbSe) (p-type) | 0.26 | 27 |
| Lead Selenide (PbSe) (n-type) | -0.29 | 27 |
| Selenium doped with copper | 1.24 | -- |

Table 3 shows some values for the figure of merit Z (as defined by Equation 5) for several semiconductors.

TABLE 3. VALUES OF FIGURE OF MERIT

| Material | Figure of Merit (per degree K) | Temperature (K) |
|---|---|---|
| PbTe (p-type) | 0.0018 | 600 |
| PbTe (n-type) | 0.0019 | 500 |
| ZnSb (p-type) | 0.0012 | 500 |
| $Bi_2Te_3$ (p-type) | 0.0022 | 300 |
| $Bi_2Te_3$ (n-type) | 0 028 | 300 |

## APPLICATION OF THERMOELECTRIC DEVICES

A variety of applications for thermoelectric effects have been developed.

### TEMPERATURE MEASUREMENT

This is an old and well-established application in science and industry. Efficiency of energy conversion is not particularly important for this application. Thus, metal wires generally are employed in this application, rather than semiconductors, since wires are more convenient to use.

### GENERATION OF ELECTRICITY

Thermoelectric generators of electricity offer the advantages of having no moving parts and of having high efficiency for small generators. Thermoelectric generators of less than a few kilowatts have efficiencies of up to 10%, a value higher than that available from conventional generators of comparable size. For larger generators, steam turbines

have efficiencies of up to 40%, and thermoelectric generators do not compete well with them. Thus, thermoelectric generators are useful for generation of electrical power in remote areas, particularly in cases in which power requirements are not too high. Thermoelectric generators have been used as sources of electrical power in Arctic weather stations, navigation buoys, oil platforms in the ocean, and unattended lighthouses.

In the rural areas of the United States, electrification was completed some time ago, and thermoelectric sources did not achieve great importance. In rural areas of the Soviet Union, however, kerosene-fueled thermoelectric generators are an important source of electrical power.

## SPACECRAFT POWER

Generation of electricity on spacecraft can be regarded as a special case. The heat source is a radioactive isotope. Such generators have been providing electrical power on orbiting spacecraft since 1961. They also have been used to power apparatus left on the moon by the Apollo astronauts.

## COOLING

Small thermoelectric coolers have been developed for a number of applications. These coolers use the Peltier effect and produce cooling directly from the flow of electric current through the device. Small, single-stage devices can produce a temperature difference of 70C°, and two-stage devices can produce temperature differences greater than 100C°. Thermoelectric coolers have found many uses for scientific applications; for example, in the cooling of electronic components, such as transistors, lasers, and infrared detectors. They are employed in the cooling of specimens for biological research.

A few consumer products using thermoelectric coolers have reached the market; for example, small refrigerators, coolers on food-serving carts, and baby-bottle coolers. The high cost of thermoelectric coolers has kept them from being used for larger refrigerators.

## HEATING

If the direction current flow in a thermoelectric cooler is reversed, the cooler becomes a heater. Thermoelectric devices have been developed for use as temperature-control devices; for example, housings for quartz-crystal oscillators have been controlled by use of thermoelectric devices to provide either heating or cooling as needed.

There have been a few consumer products, such as a "hostess cart," which provides both thermoelectric heating and cooling for different foods. Thermoelectric heating does not appear attractive for large-scale heating applications.

## SUMMARY

Thermoelectricity is the direct conversion of heat energy into electrical energy (or the reverse; that is, direct conversion of electrical energy into heat). Thermoelectric effects are observed in electrically-conducting materials through which electrical current flows. There are two broad classes of electrical conductors that show thermoelectric effects; they are metals and semiconductors. Thermoelectric effects in semiconductors are larger than in metals, so that semiconductors are used in practical thermoelectric power generators.

There are three related thermoelectric effects: (1) The Seebeck effect (the reverse of the Peltier effect) indicates that when two dissimilar metals are heated in an electrical circuit, an EMF is produced and absorbed across the junction. (2) The Peltier effect, consists of EMF developed at the heated junction. (3) The Thomson effect is the EMF produced in a metal not heated uniformly.

## THERMOELECTRIC VOLTAGE GENERATED BY A WIRE THERMOCOUPLE

### MATERIALS

Potentiometer (for example, Leeds and Northrup, model K3); a microvoltmeter may be used in place of the potentiometer.
Thermocouple wires (for example, copper-constantan or platinum-platinum plus 10% rhodium).
Beakers.
Ice.
Water.
Bunsen burner and stand.
Electric wiring, clamps, supports, drill, bit for drilling metal, metal plates, solder, and soldering iron, as needed.
Thermocouple table that gives output of a particular thermocouple. (The Handbook of Chemistry and Physics contains such tables.)

### PROCEDURE

1. Set up apparatus as illustrated in Figure 11. Use wires of common thermocouple materials; for example, copper and constantan. Twist together the ends of the wires, and solder them. A microvoltmeter may be used in place of the potentiometer, but a potentiometer will give more accurate results.

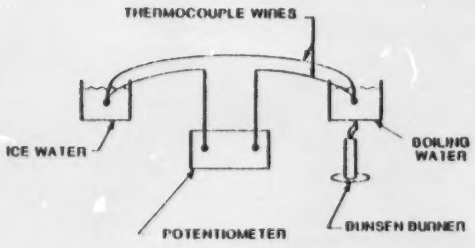

FIG. 11

2. Measure the thermally-generated EMF.

3. Use a thermocouple table that gives the output of the particular thermocouple to compare the measured value to the tabulated value.

4. Use the results of Step 2 and Equation 1 to calculate the thermoelectric power, $S_1 - S_2$, for the pair of thermocouple wires.

5. Which one of the following effects is demonstrated by this experiment? (1) The Seebeck effect? (2) the Peltier effect? or (3) the Thomson effect?

# THERMOELECTRIC VOLTAGE GENERATED BY SEMICONDUCTOR ELEMENTS

## MATERIALS

Two bars of thermoelectric semiconductor, one p-type and one n-type (for example, Lead telluride from American Smelting and Refining Co.).
Potentiometer (for example, Leeds and Northrup, Model K3); a microvoltmeter may be used in place of the potentiometer.
Thermocouple from first experiment.
Hair dryer.
Metal plates.
Beaker.
Ice.
Water.
Electrical wiring.
Drill and bit for drilling metal.
Thermocouple table as in first experiment.

## PROCEDURE

1. Set up apparatus as in Figure 12. Contact between the semiconductor bars and the metal plates is formed by firmly clamping the bars between the plates. The plates and bars must be solidly in contact. The thermocouple constructed in the first experiment is attached to upper plate. It can be embedded in a hole drilled in the plate.

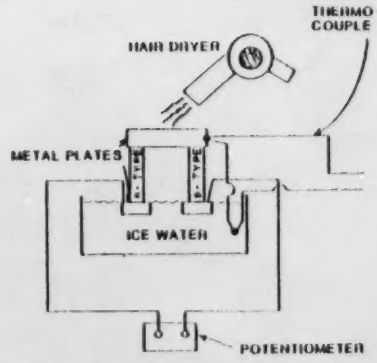

FIG. 12

2. Turn on hair dryer, and heat upper plate.

3. Measure thermoelectric voltage with potentiometer.

4. Disconnect semiconductor elements from the potentiometer, and connect thermocouple wires. Measure thermocouple voltage.

5. From Step 4 and calibration in the first experiment, determine temperature of upper plate.

6. Determine thermoelectric power, $S_1 - S_2$, for semiconductor elements. Use the results of Steps 3 and 5, along with Equation 1.

7. Compare the result from Step 6 with tabulated values. (Refer to the reference materials, or to Table 2 or Figure 10.)

## COOLING PRODUCED BY A THERMOELECTRIC COOLER

### MATERIALS

Thermoelectric cooler (available from Borg-Warner Thermoelectrics, Des Plaines, Illinois, and from Marlow Industries, Garland, Texas).
Two bars of thermoelectric material as in experiments one and two.
Thermocouple from first experiment.
Potentiometer as in experiments one and two.
Beaker.
Ice.
Water.
Battery.
Drill and bit for drilling metal.
Metal plates.
Electrical wiring.

### PROCEDURE

1. Set up apparatus as in Figure 13. The thermoelectric cooler is a commercial unit. Drill a small hole in the upper metal plate, and insert the thermocouple from first experiment. Hook up battery; make sure that voltage does not exceed maximum value specified by manufacturer.

2. Use potentiometer to determine voltage from thermocouple. Wait until top plate has cooled as much as possible.

3. Use calibration from first experiment to determine temperature of top plate.

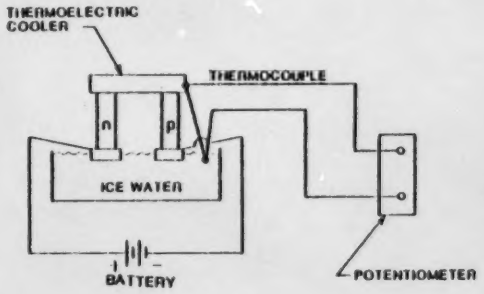


FIG. 13

4. Compare result to temperature drop claimed by manufacturer. Are there differences between the experimental results and the specified? If so, why?

## SELF CHECK

1. Describe the Seebeck effect, the Peltier effect, and the Thomson effect.

2. Name two general types of thermoelectric materials. Name at least one specific example of each.

3. Name at least four applications of thermoelectricity.

4. The Seebeck coefficient of p-type PbTe is 0.35 mV/K, and of n-type PbTe is -0.30 mV/K. If these two materials are used in a thermoelectric circuit between a hot junction at 600 K and a cold junction at 350 K, how large is the thermoelectric voltage?

5. A thermoelectric generator, with figure of merit of 0.0032/K works between a hot junction at 950 K and a cold junction at 273 K. It has its electrical resistance adjusted for optimum efficiency. What is its efficiency?

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UTC

UNIFIED TECHNICAL CONCEPTS

MODULE 9 T 3

SOLAR COLLECTORS

THERMAL APPLICATION OF ENERGY CONVERTORS

Technical Education Research Center – Southwest

TERC – SW

## INTRODUCTION

On a clear day, when the sun is directly overhead, solar energy arrives at the earth's surface at a rate of about 100 milliwatts/$cm^2$. Solar energy can be an important source of energy for space heating, water heating, cooling, industrial processing and electrical generation. This module discusses the solar collectors needed to harness this energy by converting energy from the sun into thermal or electrical energy. Solar collectors can take the form of simple, flat plates that absorb energy that heats water contained in pipes within the plates. The heated water then is used for space heating or for other applications. More advanced collectors include the concentrating time that focuses the sunlight, and the photovoltaic type.

In the laboratory, the student will construct a small section of a flat-plate collector and measure its efficiency, and will measure the conversion efficiency of a photovoltaic collector.

## PREREQUISITES

Student should have completed Concept Module 9-0, "Energy Converters."

## OBJECTIVES

Upon completion of this module, the student will be able to:

- Discuss flat-plate collectors and concentrating collectors, including these factors:

  How they are constructed.
  At least three advantages for each type.
  At least three applications for each type.

- Define solar constant, give its numerical value, and state how much energy per unit area reaches the earth's surface on a clear day when the sun is directly overhead.

- Describe how photovoltaic solar collectors operate, and in-

clude a description of the photovoltaic effect.

- Given the necessary information, calculate the conversion efficiency of flat-plate and photovoltaic collectors.
- Given the appropriate equipment, measure the efficiency of a flat-plate collector and of a photovoltaic collector.

## DISCUSSION

The sun delivers a large amount of energy to the earth in the form of electromagnetic radiation. This energy falls mostly in the visible, infrared and ultraviolet portions of the spectrum. It is, of course, responsible for the existence of life on earth. It makes plants grow. It provides much of the driving force for the circulation of the atmosphere and the oceans. Variations in the amount of solar energy reaching the earth lead to the progression of the seasons.

Energy delivered by the sun also can be employed for heating homes, offices and factories; for cooling; for water heating; and for industrial processes. The sun, thus, can be an important source of energy that can be harnessed to serve the needs of human beings. Good collectors for the incoming energy are needed. The discussion in this module concentrates on some of the more common collectors.

First, how much energy arrives from the sun? The amount reaching the vicinity of the earth (outside the earth's atmosphere) is called the "solar constant," which has a value of 135 milliwatts/cm$^2$. This number varies slightly as the earth revolves around the sun during the course of the year, but is a good average value. Thus, on a flat surface facing the sun and located above the atmosphere, each square centimeter (cm) would be insolated by 135 milliwatts. The word "insolation" shall be used to describe delivery of solar energy.

Some of the incident energy is lost during passage of light through the atmosphere. Some light is absorbed by molecules in the atmos phere; other light is scattered in such a manner that it changes direction. Some of the scattered light reaches the surface of the earth, but it will not be in the form of the direction beam from the sun.

Figure 1 shows, in a simplified way, the effects of the passage of sunlight through the atmosphere. Figure 1 plots the relative fraction of incident energy per unit area versus the wavelength. (Visible light covers the wave length range from 0.4 to 0.7 micrometers. Ultraviolet light has shorter wavelengths, and infrared radiation has longer wavelengths.) The reduction by the atmosphere of the energy

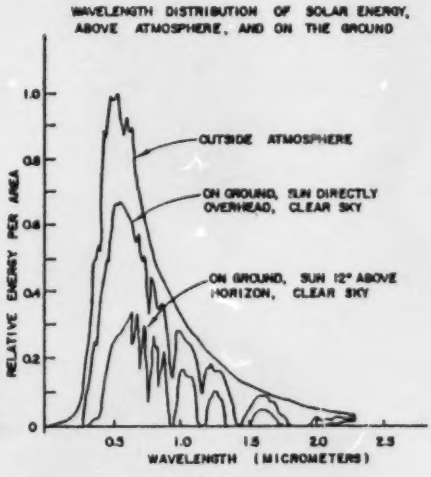



FIG. 1

reaching the surface is obvious. As the sun gets closer to the horizon, the energy must pass through a thicker layer of atmosphere, and less energy reaches the surface. If haze or clouds are present, the incident energy will be reduced even more than Figure 1 indicates. Figure 1 is also important for defining some of the properties of the collector. The solar collector must absorb at wavelengths for which the solar energy reaches the ground.

The dips in the curves for energy reaching the ground as compared to energy outside the atmosphere are attributable to absorption by various molecules present in the atmosphere.

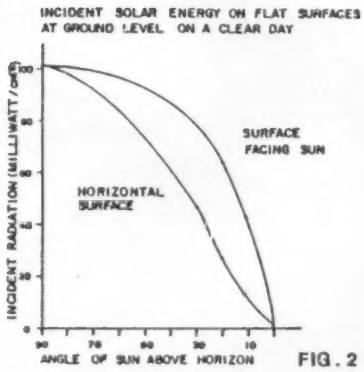


FIG. 2

Figure 2 shows the energy per unit area striking a flat area on the earth's surface on a clear day, versus the angle of the sun above the horizon. A surface tilted to face the sun can receive considerably more energy than a horizontal surface. Even in the best circumstance (that is, when the sun is directly overhead), the 135 milliwatts/cm$^2$ which reaches the top of the atmosphere is reduced to about 100 milliwatts/cm$^2$ by passage through the atmosphere. This value is equal to about 1 kW/m$^2$.

The total energy reaching the surface of the earth during the course of a year is impressive. Figure 3 shows the annual insolation over the United States. It is greatest in the Southwest; but even in the Northeast, it represents a large, potentially-useful energy source. If properly utilized, solar energy could reduce demands on other energy supplies.

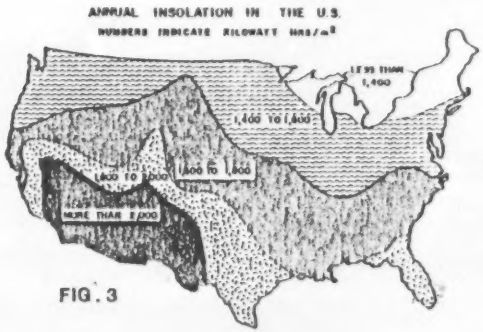


FIG. 3

## FLAT-PLATE COLLECTORS

The most simple and basic collector is the flat-plate type, shown schematically in Figure 4. The absorbing surface collects the incident energy and thereby is heated. The tubes below the absorbing surface contain a fluid, usually water, that is circulated to deliver heat to an external source as needed. The transparent cover on the top allows incident light to reach the absorbing surface, but reduces reflective or radiative losses back to the atmosphere. The insulation on the back reduces heat loss by conduction. This simple, basic design has many variations,

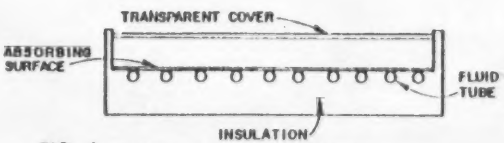


FIG. 4 BASIC FLAT-PLATE COLLECTOR

but the more important features are illustrated in Figure 4.

The materials used in the flat-plate collector are important. Flat, black paint can be used for the absorbing surface, but efficiency can be increased by the use of selective absorbers, which absorb efficiently in the wavelength regions in which solar energy is concentrated. (See Figure 1.) Research is still underway to develop optimum materials for use in flat-plate collectors. With present technology, conversion efficiency of 50-60% from incident solar energy to thermal energy is possible with flat-plate collectors.

Figure 5 shows how a flat-plate collector could be used to provide space and water heating in a home. The collector is mounted on the roof, facing south and tilted to face the sun as much as possible. Pumps circulate the heated fluid as needed. The heat-storage reservoir could be a water tank. The heated water is circulated through the storage reservoir in pipes, and heats the water in the reservoir. This water, in turn, circulates through pipes in the house to provide space heating. Heated water direct from the collector is circulated through a water heater to heat water for home use.

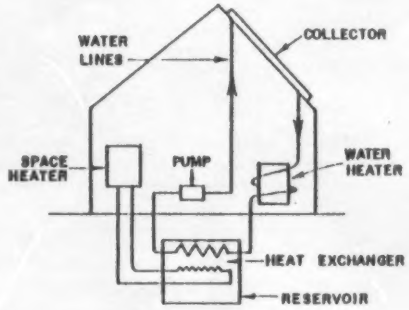



FIG. 5

There are several practical considerations that should be mentioned. First, a back-up conventional heating system probably will be needed in many areas, where a series of cold, cloudy days could make the solar heating system ineffective. Second, the water in the collector probably will cool to below freezing at night; therefore, a mixture of antifreeze and water normally is used. Finally, corrosion is a significant practical problem in working systems; therefore, corrosion inhibitors often are added to the water. The use of air as the heated fluid would eliminate the last two problems, but air is less efficient than water as a medium for heat exchange.

Solar energy also can be used to drive cooling systems. The cooling system is the same as that for a a gas refrigerator or air conditioner. The heated water takes the place of the flame in the gas refrigerator. Solar air conditioners of this type have been developed.

The temperature that can be reached with flat-plate collectors with current technology is around 150-200°C. This range is adequate for many practical applications. The applications that are now in use include the following:

- Space heating.
- Water heating.

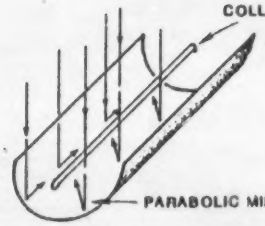
- Air conditioning.
- Industrial-process heat and industrial-process steam.

The cost of flat-plate solar collectors can be low enough to be competitive with conventional fuels. The exact comparison becomes complicated, and depends upon the climate in which it is used, costs for labor and materials, values for interest rates, payback rate for the initial investment and prices of conventional fuels in the future. For space heating, solar systems can be less costly than electrical heat or oil heat in the late 1970s, but probably still more expensive than heating with natural gas. As the price of natural gas rises in the future, however, solar heating probably will be less expensive than gas.

For water heating, solar heating is economically attractive in the late 1970s, compared to all three conventional fuels, because the system would be in use year-round. Reasonable estimates for the price of solar heating systems based upon flat-plate collectors are in a range of from $2 to $4 per square foot of collector. The National Aeronautics and Space Agency (NASA) has designed a system to heat a 1500-square-foot house for about $2,040, based upon the dollar cost of materials in 1975. The estimation has been made that the installation could pay for itself in 10 years.

## CONCENTRATING COLLECTORS

Because the temperature that can be reached with flat-plate collectors is limited, concentrating (or focusing) collectors sometimes are used. Such collectors utilize mirrors or other structures to focus solar radiation striking a large area onto an absorber of smaller area, which allows production of higher temperatures. One possible design of a concentrating collector is shown in Figure 6. A cylindrical reflecting mirror with a parabolic cross-section reflects the sunlight and focuses it onto a collecting pipe. The pipe is filled with a fluid (usually not water, because of the high temperatures reached). The fluid may be air or a molten salt. The pipe is surrounded by a quartz or glass envelope to reduce heat losses. The design shown in Figure 6 is one simple arrangement, but there are many other possible designs for concentrating collectors.




EXAMPLE OF FOCUSING COLLECTOR

FIG. 6

The temperature that can be reached in the collecting tube is much higher than that reached with flat-plate collectors. Temperatures up to 500°C are not difficult to produce within the pipe. In some research models, temperatures up to a few thousand degrees °C have been obtained. The efficiency of a concentrating collector can be higher than that for a flat-plate collector. It can range up to 75%. Thus, for a given, required power output, the size of the collector can be smaller if a concentrating collector is used.

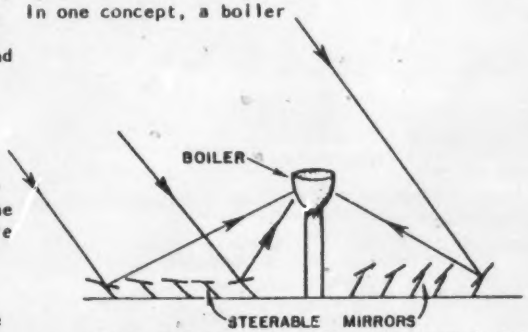
Concentrating collectors must track the sun, in order that the image of the sun is forcused accurately upon the absorber. Thus, they are mounted on movable mounts, and are equipped with solar sensors to move the collectors to follow the sun across the sky. Also, they depend upon a well-defined solar image, so that they almost are completely ineffective on a cloudy or a hazy day. Flat-plate collectors, on the other hand, will collect the diffuse radiation from the sky on a cloudy day, and will delivery some output.

Table 1 summarizes the relative advantages of flat-plate and concentrating collectors.

TABLE 1: RELATIVE ADVANTAGES OF FLAT PLATE AND CONCENTRATING COLLECTORS

| Flat-Plate Collector | Concentrating Collector |
|---|---|
| Simpler construction | Higher efficiency |
| No need to track sun | Higher temperatures possible |
| Ability to use diffuse sky radiation | Smaller areas needed |

Concentrating collectors can be employed for electrical power generation at a large, central station. In one concept, a boiler is mounted on a tower. A large number of mirrors covering a large area of land focus sunlight onto the boiler. The mirrors are steered independently by solar sensors. The concept is shown schematically in Figure 7. Solar power towers capable of driving turbines and generating megawatts of electrical power are under development. The mirrors may be spread over areas of more than a square mile.



TOWER CONCEPT FOR SOLAR POWER GENERATION

FIG. 7

In summary, possible applications of concentrating collectors include the following:

- Generation of industrial-process heat and steam at higher temperature than flat-plate collectors can provide.
- Cooking. Simple solar concentrators are in wide-spread use for cooking in many underdeveloped countries.
- Direct electrical-power generation.

## PHOTOVOLTAIC COLLECTORS

The technology of solar collectors in practical use in the late 1970s is based upon the flat-plate and concentrating absorbers described above. The rapid development of photovoltaic collectors, however, offers the promise of direct generation of electricity from sunlight. Such systems may become practical and economical in the 1980s. The use of photovoltaic devices to generate electricity for spacecraft has been well-known for many years. However, such solar cells have been too costly for terrestrial applications. New manufacturing techniques now offer the possibility of economical production of large-area solar cells that could be used to generate electricity on the earth's surface.

As discussed in Application Module 9E6, "Photovoltaic Materials," the photovoltaic effect is produced as follows: At a junction between P-type and N-type semiconductor materials, there is an electric field in the semiconductor. When light is absorbed at the junction, it produces free electrical current carriers (electrons and holes) that move under the action of the electric field. This process produces an electric current. The photovoltaic effect allows direct conversion of the energy in sunlight to electrical energy. There is no need for an externally-applied voltage source.

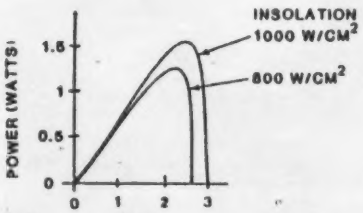


FIG. 8

Some characteristics of a silicon solar cell are shown in Figure 8, which shows the power output from a solar cell array of area around 20 $cm^2$ under two conditions of insolation. The maximum power is extracted at a particular level of voltage; at higher voltages the power drops off rapidly. The characteristics shown in Figure 8 are representative of what is available from state-of-the-art commercial devices.

The solar cells used on spacecraft were made of single-crystalline silicon. Silicon itself is inexpensive, since it is the second most common element in the earth's crust, although processing costs were high, involving growth of a single crystal of silicon with high perfection. Now techniques are under development for making large areas of silicon solar cells inexpensively. The techniques include the dipping of a ceramic substrate into molten silicon to coat it with a thin layer. Other possibilities include the painting or spraying of silicon onto a substrate.

The key figure is the cost of the silicon solar cell. In order to make this technology economically feasible for terrestrial use, the cost of the solar cell must be reduced to about 50¢ per watt of electrical power. There is a large national program aimed at meeting this cost goal in the 1980s.

The low-cost solar cells described above could provide electrical generation for the home. A typical home might use about

600 kilowatthours of electricity each month. A photovoltaic system with a peak output of 5000 watts could meet this demand. In many parts of the country, a photovoltaic array with a working area of around 400 sq ft would be adequate. A battery storage system would be needed to carry over through the night.

Large area installations, perhaps in the southwestern United States, also would be possible for central power stations. Such systems covering hundreds of square miles in remote areas have been suggested. Such installations would be capable of generating a significant fraction of the electrical power requirements of the western United States.

The efficiency that has been demonstrated for large-area silicon solar cells is around 12-14%. Another possibility is gallium arsenide, which has a spectral response better matched to the solar spectrum shown in Figure 1. Gallium arsenide solar cells can achieve conversion efficiencies up of to 21%. They would be more expensive than silicon.

Solar photovoltaic systems offer a potential for providing significant amounts of electrical energy directly from sunlight. This conversion is clean and silent, and involves no heat engine and no moving parts. Its success will depend upon advances in manufacturing technology that will allow the production of solar cells at low cost.

## SUMMARY

Solar collectors convert the energy of light radiation into thermal energy or into electrical energy. Flat-plate and concentrating (focused) collectors produce thermal energy in the fluid circulating through them; whereas, photovolaic collectors convert light radiation directly into electrical energy.

## EFFICIENCY OF A FLAT-PLATE COLLECTOR

### MATERIALS

Absorbing Material. (Foamglas absorber, 1½" slabs, sold by Pittsburgh Corning Corp., One Gateway Center, Pittsburgh, PA 15222, for 35¢/sq ft. Alternative: Roll-Bond Solar absorber. Sold by Olin Brass, East Alton, IL 62024, at $41.75 for 34 x 96" aluminum material, plus $25 packing fee for quantities under 50.)
Glazing material. (Kal-Lite fiberglass, 0.040" thick, from Kalwall Corp., Box 237, Manchester, NH 03105, at 40¢/sq ft.)
Wood (2" x 4" framing).
Duct tape.
Hammer, nails, saw and drill.
Flat-black spray paint.
Thermometer.
Pyranometer — desirable but not essential. Module 8-48 from the Eppley Laboratory, Newport, RI 02840, is suitable; cost $590.
Wristwatch.
Meter stick.

### PROCEDURE

The purpose of this experiment is to construct a simple solar absorber, and to measure its efficiency.

1. Construct a simple solar absorber panel, according to the diagram in Figure 9. Many other types of absorbing materials and structures could be used but the design in Figure 9 is typical, and will illustrate the principles. The Foamglas absorber is suggested as a relatively inexpensive absorbing material. It also has the built-in insulator. Grooves help trap incident sunlight. The working fluid is air. Build a frame of 2 x 4 wood. Cut the Foamglas to size, and insert in the frame. Cut the glazing material to size, and attach to the top of the frame with duct tape. Drill a hole in the end of frame. Insert the thermometer through the hole in such a manner that its end is in air space above the absorber.

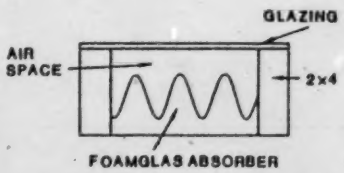


FIG. 9

2. The remainder of this experiment should be carried out on a clear, sunny day. Use pyranometer to measure the intensity

of the incident solar radiation. Record value in Data Table 1. If a pyranometer is not available, use Figure 2 to estimate intensity.

3. Move the absorber into sunlight. Place it horizontally on ground. In Data Table 1, record initial temperature reading of thermometer. After a few minutes, when temperature has risen perceptibly, record temperature again. Record elapsed time in seconds.

4. Move absorber inside, and allow it to cool to room temperature. Then move it back into the sun, and tilt it so that it faces the sun directly. Repeat step 3.

5. Move absorber inside. Allow it to cool to room temperature. Remove duct tape and glazing, and spray paint absorber black. Allow paint to dry. Reinstall glazing and duct tape. Move absorber back into sun, and tilt so that it faces the sun directly. Repeat step 3.

6. Measure volume of the working fluid in the absorber. Volume V is approximately $V = \ell w (h_1 + \frac{1}{3} h_2)$ where $\ell$ is length of absorber, w is its width, $h_1$ is height from the glazing to top of absorber, and $h_2$ is depth of grooves in absorber. Measure these dimensions with meter-stick; record. Calculate V and record.

7. Fill out Data Table, and calculate efficiency $\eta$. As indicated in the Data Table, efficiency is defined simply as the ratio of energy absorbed by the heated air to energy delivered by the sun. The procedure, as outlined, allows measurement of absorbed energy as air is beginning to heat, when air is not far above ambient temperature. Measurement at this time minimizes losses due to conduction and reradiation. It allows measurement of transfer efficiency of solar energy.

8. How does the efficiency change as absorber is tilted from horizontal and pointed directly at the sun? How does it change as absorption is increased by black paint?

## EFFICIENCY OF A PHOTOVOLTAIC COLLECTOR

### MATERIALS

Photovoltaic silicon cell. (Model PIN-10DP [$49.00] from United Detector Technology, Santa Monica, CA, would be suitable.)
Voltmeter.
Ammeter.
Meter stick.
Operational Amplifier (Op Amp).

## PROCEDURE

This experiment measures the efficiency of a silicon photovoltaic cell for sunlight.

1. Connect photovoltaic cell as indicated in Figure 10.

2. Point cell directly at sun. Measure current I and voltage V. Determine output power from this equation: $P = IV$.

3. Measure incident solar intensity with pyranometer. If a pyranometer is not available, estimate using Figure 2.

4. Measure area of photovoltaic cell (or use manufacturer's specification for area if available.).

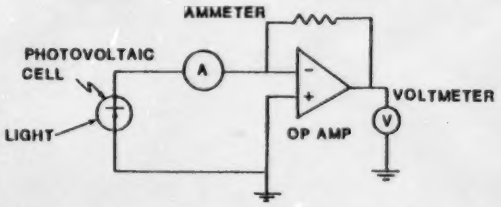


FIG. 10

5. Determine solar power incident on detector. (Area x result of step 3.)

6. Determine efficiency. (Step 2 divided by step 5.)

7. How does the efficiency of this photovoltaic collector compare with that of the flat-plate collector?

## DATA TABLE 1: FLAT-PLATE COLLECTOR

Incident Energy (Solar)

(a) Incident solar radiation _____ watts/$cm^2$ (from pyranometer)

(b) Area of solar panel _____ $cm^2$ (from measured ℓ w)

(c) Time recorded for temperature change measured below _____ (See data below.)

(d) Incident energy = (a) _____ x (b) _____ x (c) _____ = _____ Joules.

Absorbed Energy (Working Fluid is Air)

| | (a) Solar Panel Horizontal | (b) Solar Panel Tilted | (c) Solar Panel Tilted/Sprayed |
|---|---|---|---|
| Initial Temperature $T_1$ | _____ °C | _____ °C | _____ °C |
| Final Temperature $T_2$ | _____ °C | _____ °C | _____ °C |
| Elapsed time $\Delta t$ between $T_2$ and $T_1$ | _____ s | _____ s | _____ s |
| Volume V of heated air $V = \ell w (h_1 + \frac{h_2}{2})$ | _____ $cm^3$ | _____ $cm^3$ | _____ $cm^3$ |
| Mass m of heated air $(\rho_{air} V)$ $(\rho_{air} = 0.00129$ $gm/cm^3)$ | _____ gm | _____ gm | _____ gm |
| Specific heat $c_{air}$ of air $(\frac{cal}{gm \cdot C^\circ})$ $(c_V c_{air}) = 0.173$ $cal/gm \cdot C^\circ)$ | _____ $\frac{cal}{gm \cdot C^\circ}$ | _____ $\frac{cal}{gm \cdot C^\circ}$ | _____ $\frac{cal}{gm \cdot C^\circ}$ |
| Absorbed Energy | $Q_a = MC\Delta T$ = _____ cal<br>$Q_a$ = _____ cal<br>x $4.18 \frac{J}{cal}$<br>$Q_a$ = _____ J | $Q_b = MC\Delta T$ = _____ cal<br>$Q_b$ = _____ cal<br>x $4.18 \frac{J}{cal}$<br>$Q_b$ = _____ J | $Q_c = MC\Delta T$ = _____ cal<br>$Q_c$ = _____ cal<br>x $4.18 \frac{J}{cal}$<br>$Q_c$ = _____ J |
| Efficiency | $\eta \equiv \frac{Q_a}{E_{incident}}$ = _____ (See d above.) | $\eta \equiv \frac{Q_b}{E_{incident}}$ = _____ | $\eta \equiv \frac{Q_c}{E_{incident}}$ = _____ |

| DATA TABLE 2: PHOTOVOLTAIC COLLECTOR | | | | | | |
|---|---|---|---|---|---|---|
| Current I | Voltage V | Power P | Incident Solar Intensity | Area of Cell A | Solar Power Incident on Detector | Efficiency η |
| | | | | | | |

## SELF CHECK

1. Discuss flat-plate collectors and concentrating collectors. Include a description of how each is constructed, at least three advantages for each type and at least three applications for each type.

2. Define the solar constant. State its numerical value. State how much solar energy per unit area reaches the earth's surface on a clear day when the sun is directly overhead.

3. Describe how photovoltaic solar collectors operate; include a description of the photovoltaic effect.

4. A flat-plate solar collector has an area of 10 square meters; and it is pointed directly at the sun, which is 45° above the horizon. The collector, with its associated equipment, generates an output power of 5 kilowatts. What is its efficiency?

   HINT: Use Figure 2.

5. A photovoltaic collector has an area of 120 $cm^2$. When 100 milliwatts/$cm^2$ of solar radiation is incident on it, it generates 0.7 amperes of electrical current at a voltage of 2 volts. What is the efficiency of the collector?

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